The Physics Reach of the Current Long-baseline Experimental Program

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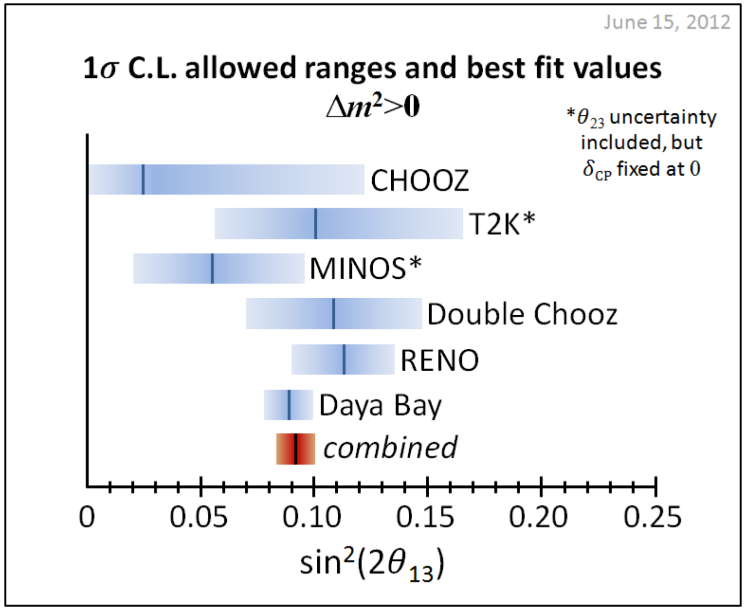
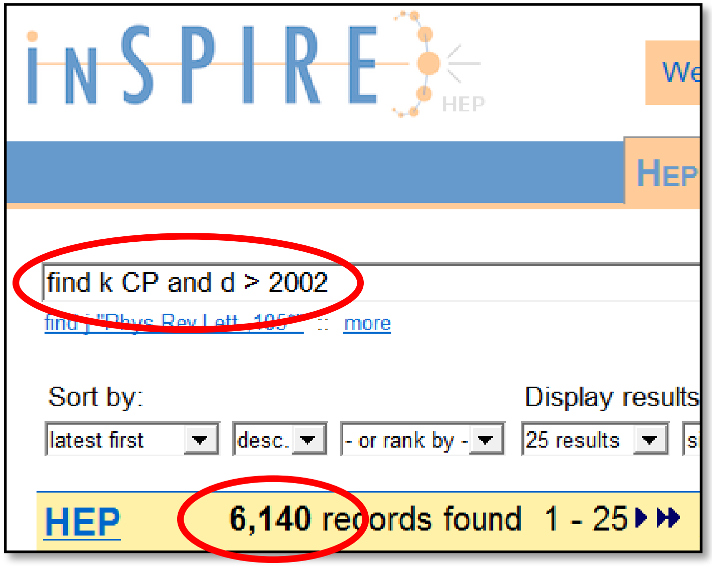
θ_{13} – the great facilitator

- **Non-zero θ_{13} is clearly established ⟶**
  Modern reactor expt. combination:
  $\sin^2(2\theta_{13}) = 0.095 \pm 0.010$
- **Makes feasible long-baseline measurements of…**
  neutrino mass hierarchy
  (0$\nu\beta\beta$ data and Majorana nature of ν; approach to m_β; cosmology; astrophysics; theoretical frameworks for mass generation, quark/lepton unification; Is the lightest charged lepton associated with the heaviest light neutrino?; …)
  CP phase δ
  (Most vocalized motivation is the relation to the cosmological baryon asymmetry though leptogenesis, but even this huge motivation understates the importance of searching for CP violation in leptons, as evidenced here) ⟶
  ν_3 flavor mixing
  (Is ν_3 more strongly coupled to μ or τ flavor?; frameworks for mass generation, quark/lepton unification; …)

θ_{13} is not the end. It is the beginning.

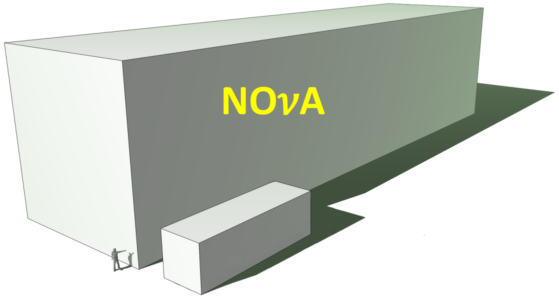


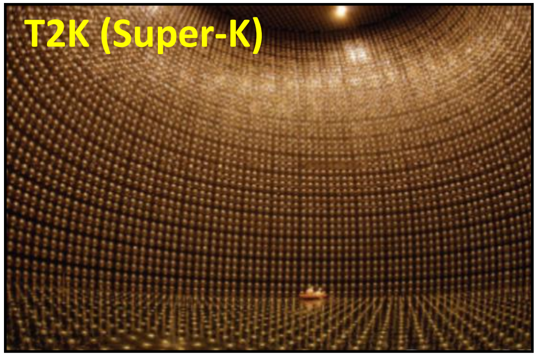


- **Of note, intriguingly specific predictions for mixing matrix relationships are out in the wild…**

Current long-baseline experiments

- **Making a stab at these questions:**
  MINOS, NOνA, T2K
  (presented in pedagogically convenient order)
- ***Also included in these experiments' goals:***
  - **precision measurements of dominant atmospheric parameters $|\Delta m^2_{atm}|$, $\sin^2(2\theta_{23})$**
  - **comparisons of ν, $\overline{\nu}$ disappearance (BSM physics)**
  - **sterile searches, supernovae, cross sections, …**
- **Will discuss separate and combined reaches**
- **Other current LBL experiments are somewhat orthogonal in scope. I won't talk about them:**
  OPERA (ν_τ appearance, ToF, …)
  ICARUS (LAr R&D, ν_τ appearance, steriles, …)



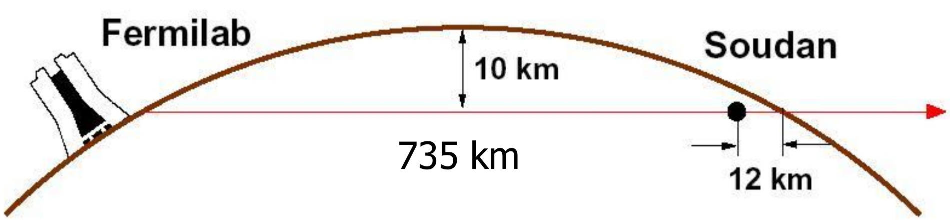


MINOS

- NuMI to Soudan (735 km)
- Iron-scintillator tracking calorimeter
- Best-suited for ν_μ CC channels (disappearance measurements)
- But, can do θ_{13}-driven ν_e appearance, too

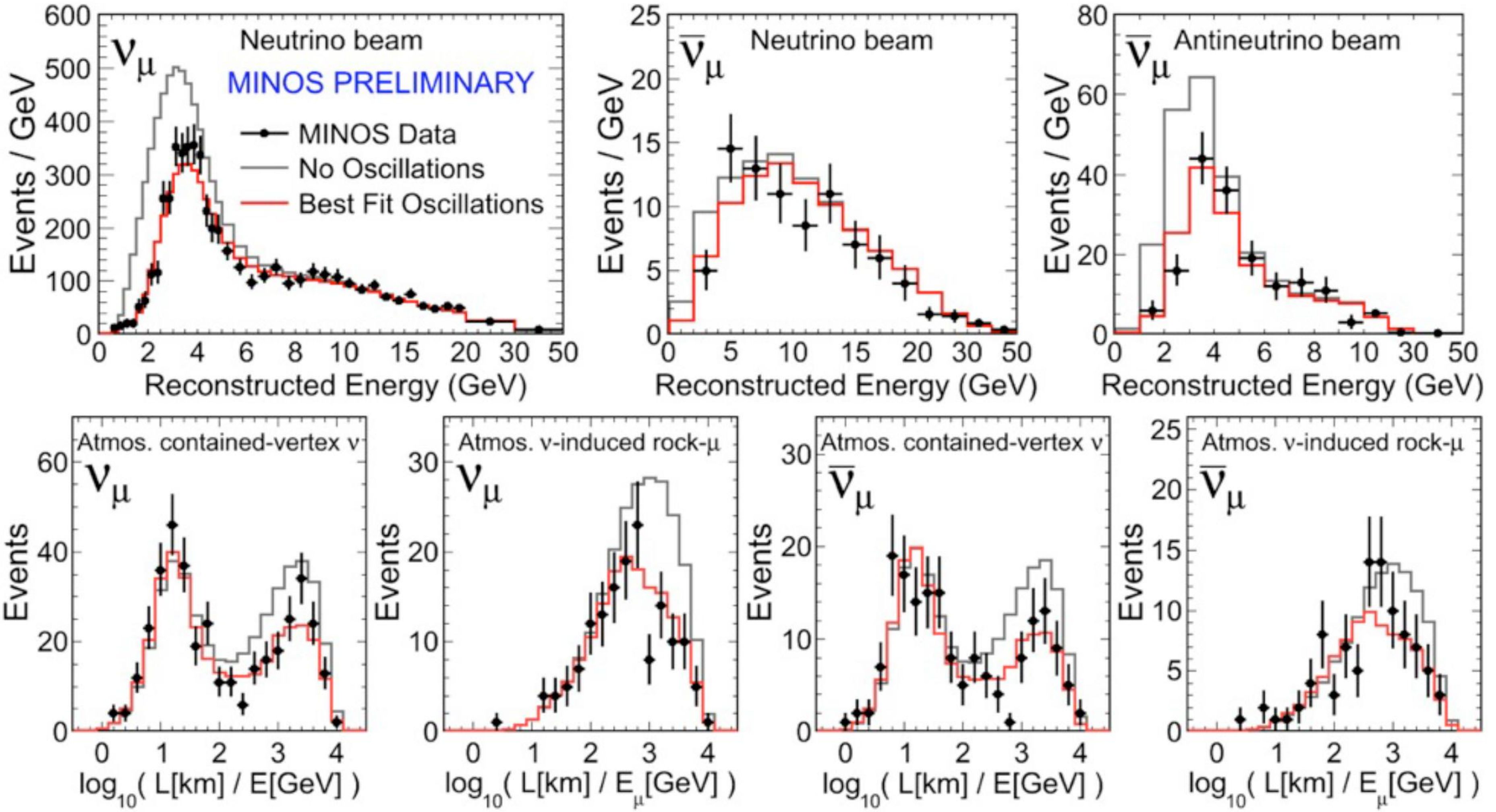
"Identical" near and far detectors
(1 kton ND, 5.4 kton FD)

MINOS primary physics run is over
(however, see MINOS+ talk)



Full, everything-combined (almost) ν_μ CC data set
(from MINOS talk at Neutrino 2012)

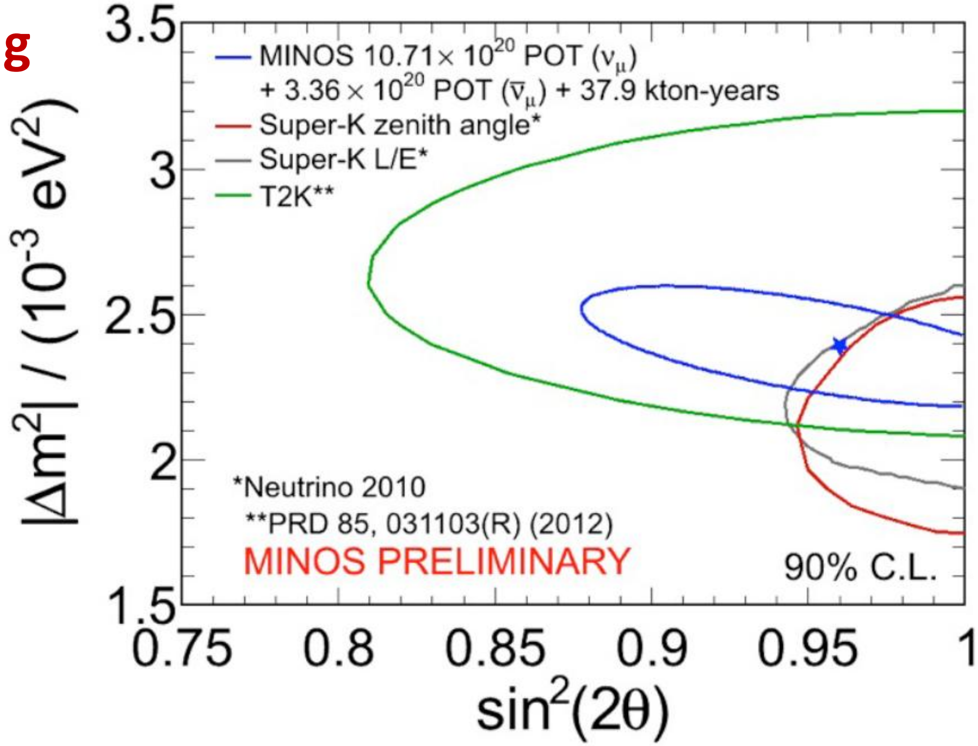
ν_μ / anti-ν_μ / anti-ν_μ in anti-ν_μ mode / atmospheric ν_μ and anti-ν_μ



MINOS ν_μ disappearance

- **~4% error on squared-mass splitting**
  (Note: $|\Delta m^2_{21} / \Delta m^2_{32}| \approx 3\%$
  ⇨ precision, 3-flavor era)

- ***Best-fit:* non-maximal mixing**
  - Only at 1σ, but relevant for discussion later
  - New Super-K atmospheric result at Neutrino 2012 also prefers non-maximal mixing



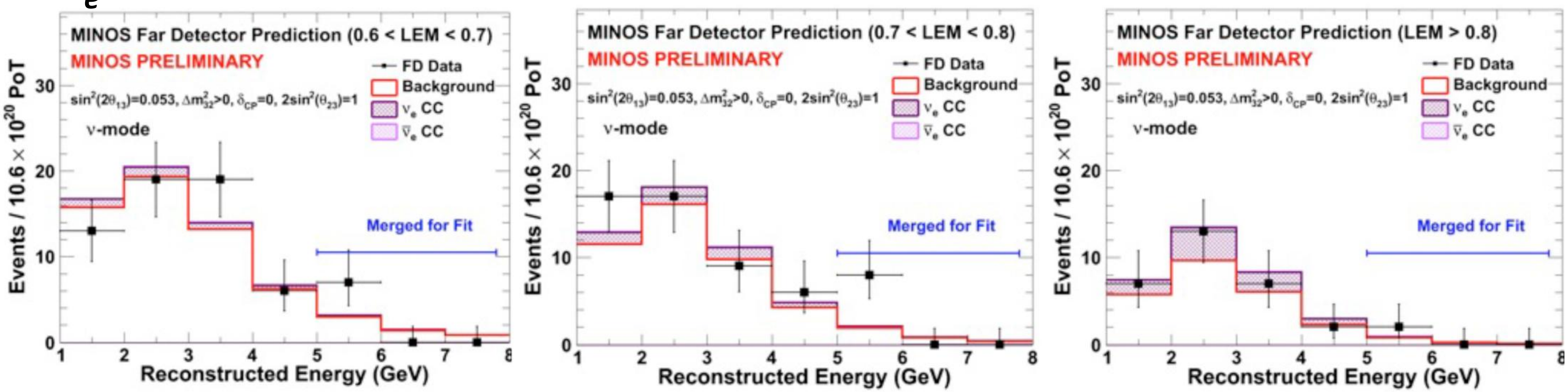
$$|\Delta m^2_{atm}| = (2.39^{+0.09}_{-0.10}) \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(2\theta_{23}) = 0.96 \pm 0.04$$
$$\sin^2(2\theta_{23}) > 0.90 \ (90\%\ \mathrm{C.L.})$$

MINOS ν_e appearance

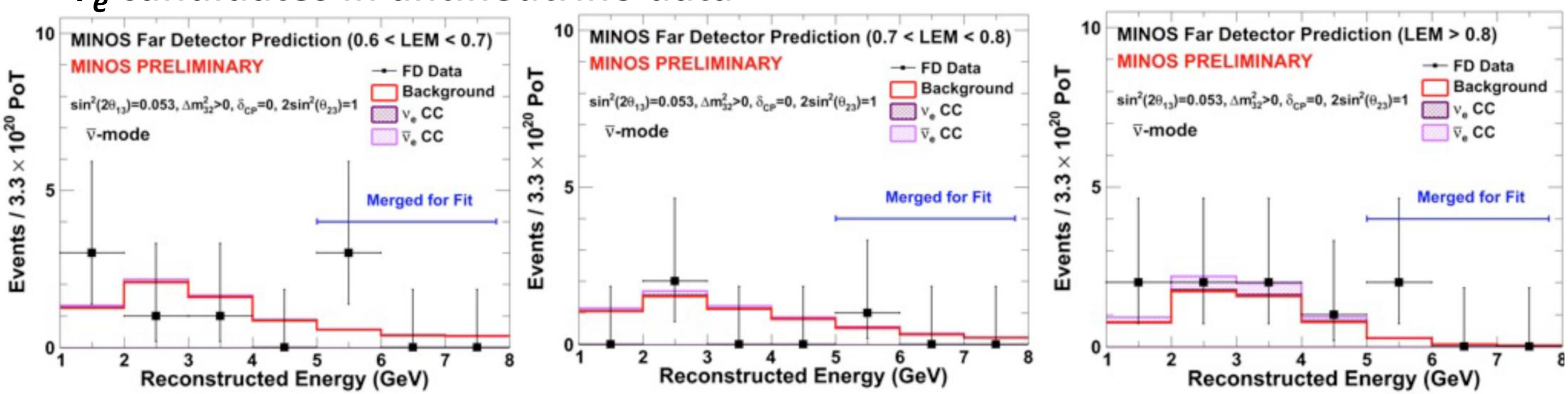
From MINOS talk at 2012

Full neutrino and antineutrino data sets combined

ν_e candidates in neutrino data



$\bar{\nu}_e$ candidates in antineutrino data



MINOS ν_e appearance

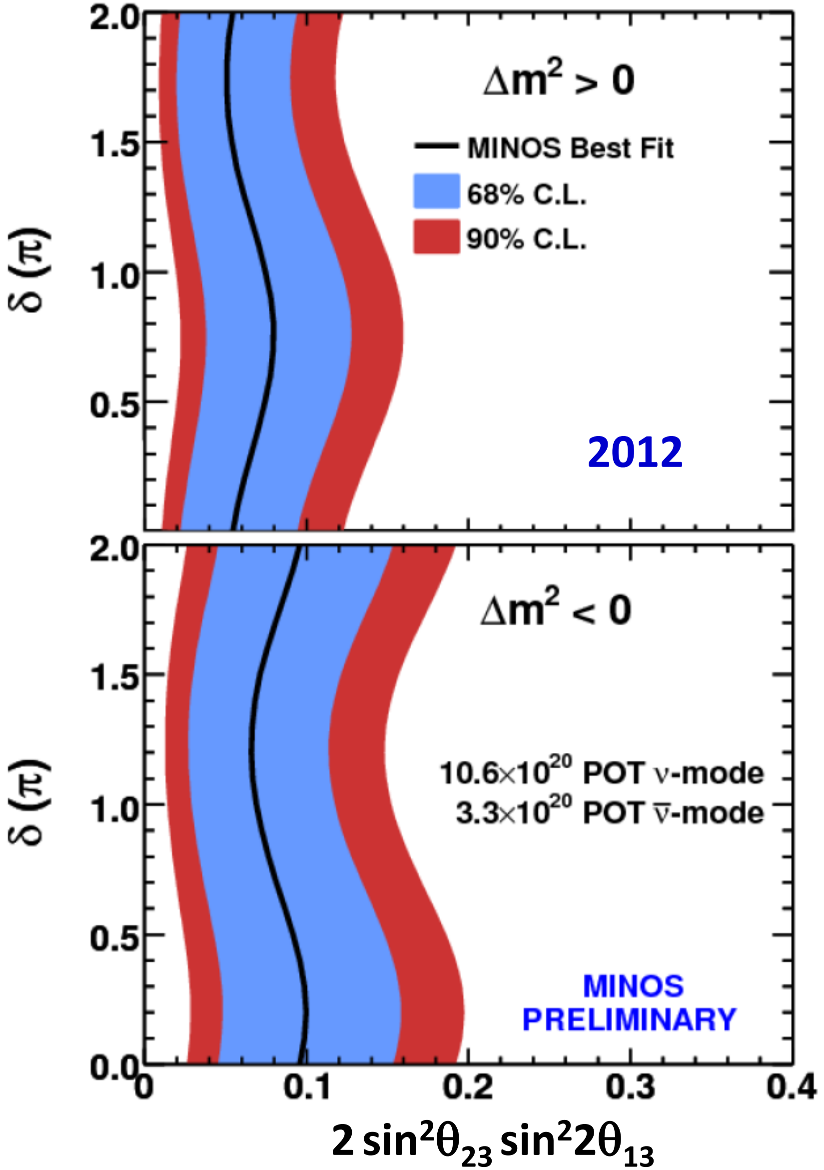
- **Result will probably not improve competitively in MINOS+ era. (MINOS+ spectrum not very favorable for ν_e appearance measurement.)**
  - ⇨ ***This is basically the final word.***
- **ν_e appearance significance: 96% C.L.**
  1st-generation, iron-based, broadband-spectrum experiment: remarkable that this can be done!

MINOS (at δ=0, θ_{23}=45°)

$\sin^2 2\theta_{13} = 0.06^{+0.04}_{-0.04}$ (normal hier.)

$\sin^2 2\theta_{13} = 0.10^{+0.06}_{-0.06}$ (inverted hier.)

- **δ and hierarchy dependence visible in contours at right. What does the MINOS result tell us about the mass hierarchy?**
  (Getting a little ahead of myself, but…)

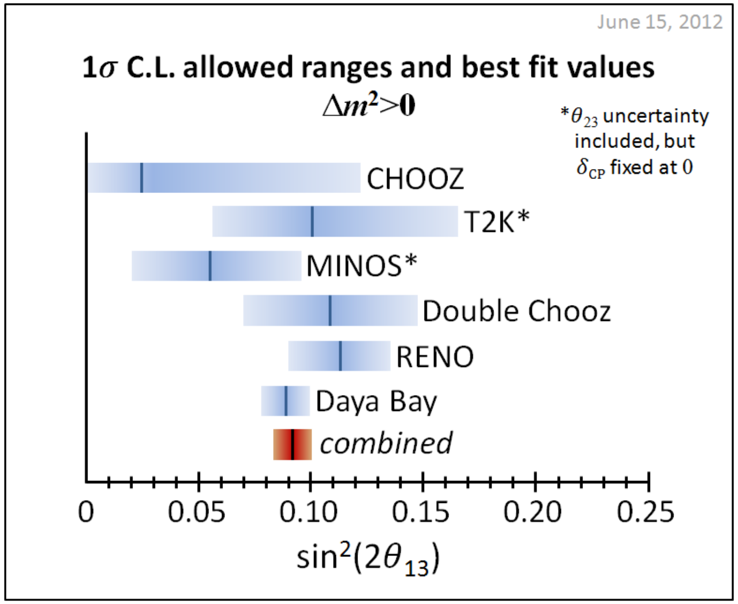


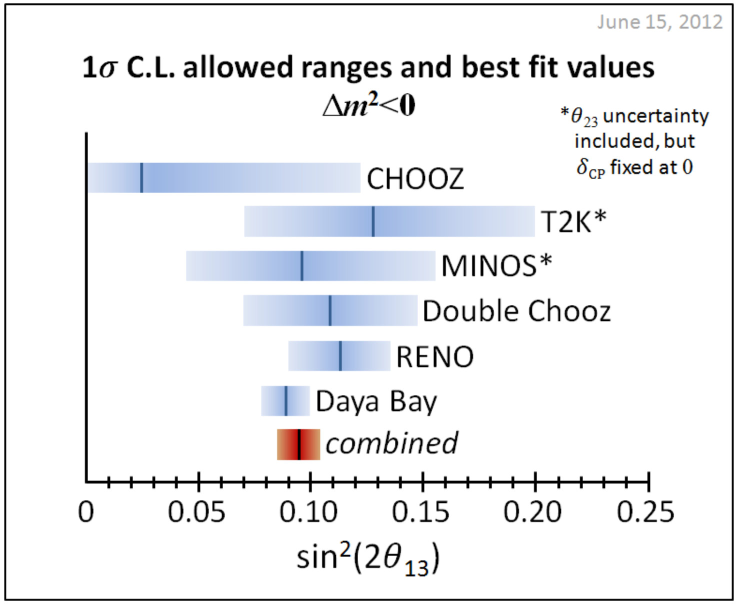
MINOS ν_e appearance – hierarchy?

Qualitative idea is evident here:

(MINOS ranges vs. combined range)

Quantitatively?





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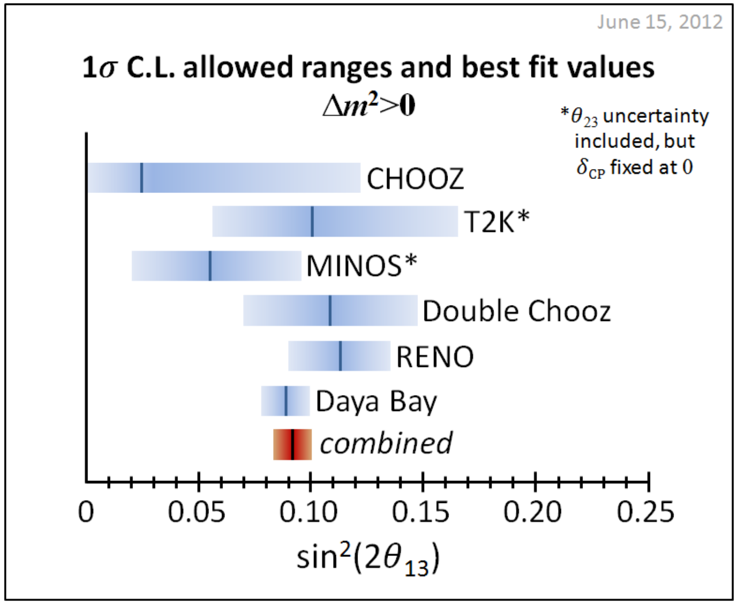

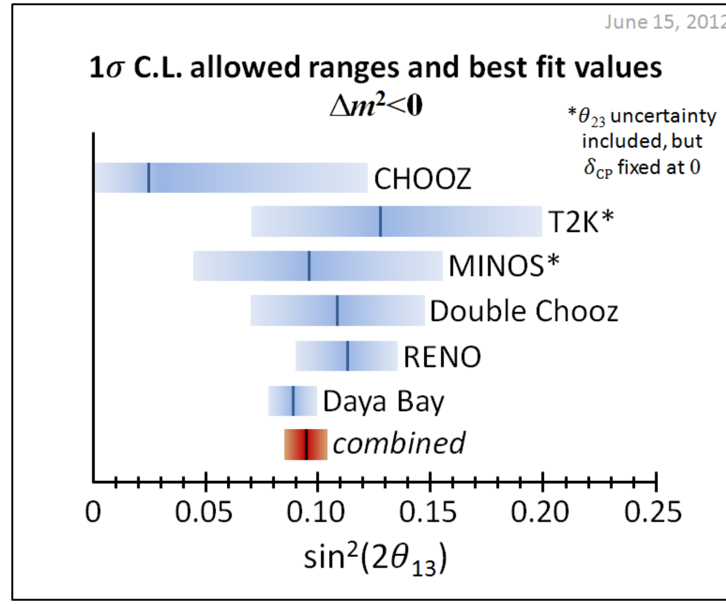

Quantitatively?

- **Today: must marginalize over θ_{13}, θ_{23}, & δ; pull terms on θ_{13}, θ_{23} w/ current errors:**
  The MINOS data prefer inverted hierarchy at 0.20σ
  (so, not much preference)

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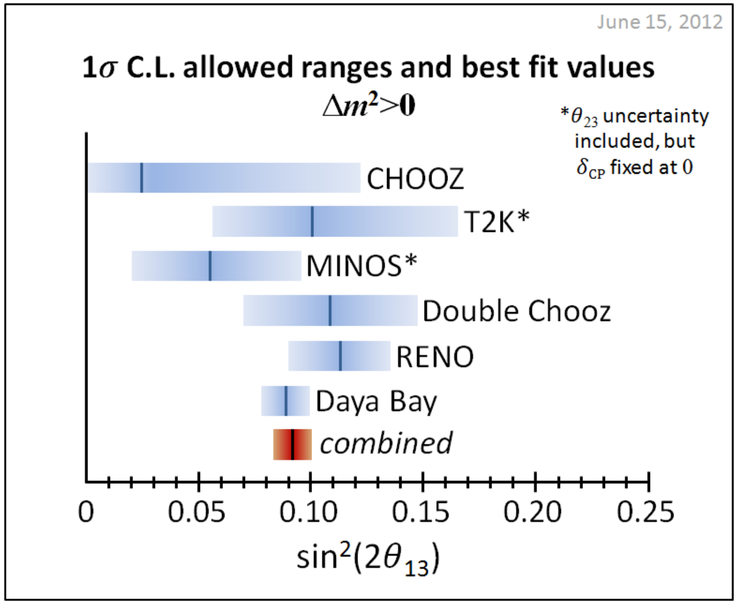

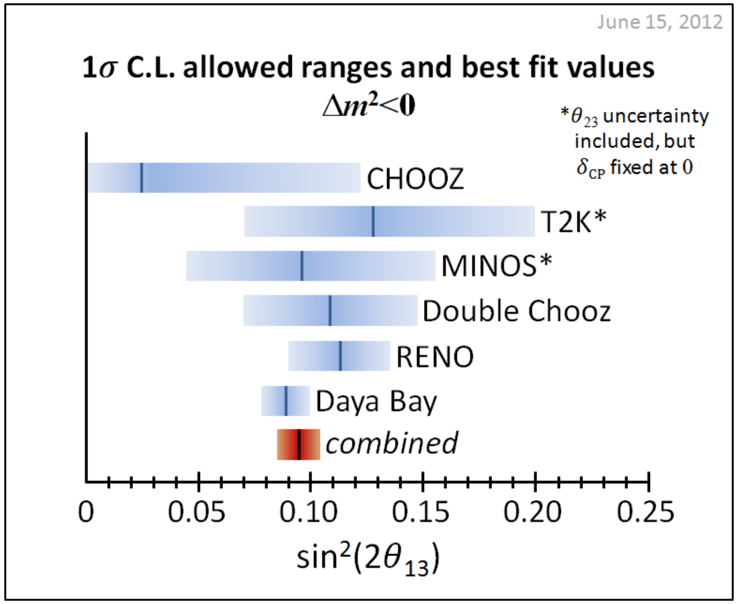

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- **Future:** **Will soon enough know θ_{13} and θ_{23} very well. Assume $\sin^2(2\theta_{23})=1$ and $\sin^2(2\theta_{13})=0.095$, and marginalize over δ:**
  The MINOS data would prefer inverted hierarchy at 0.24σ
  (This is the approximate impact at the time of full T2K and NOνA exposures.)

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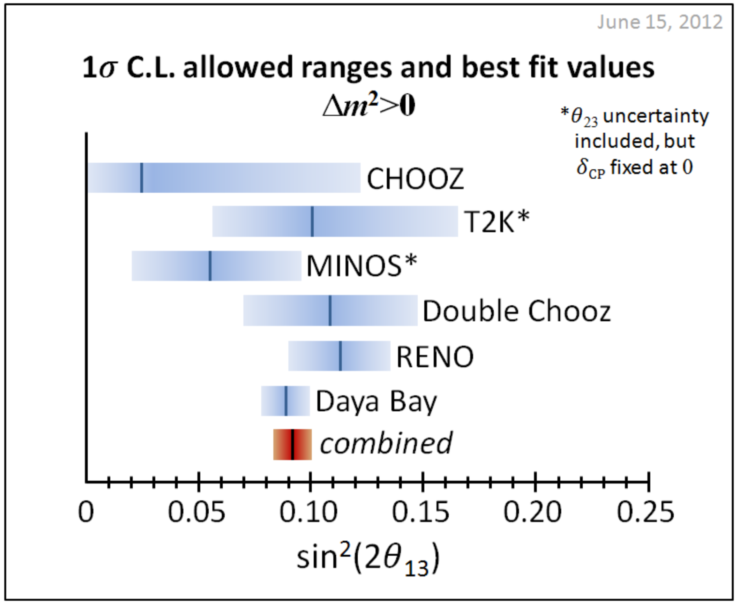

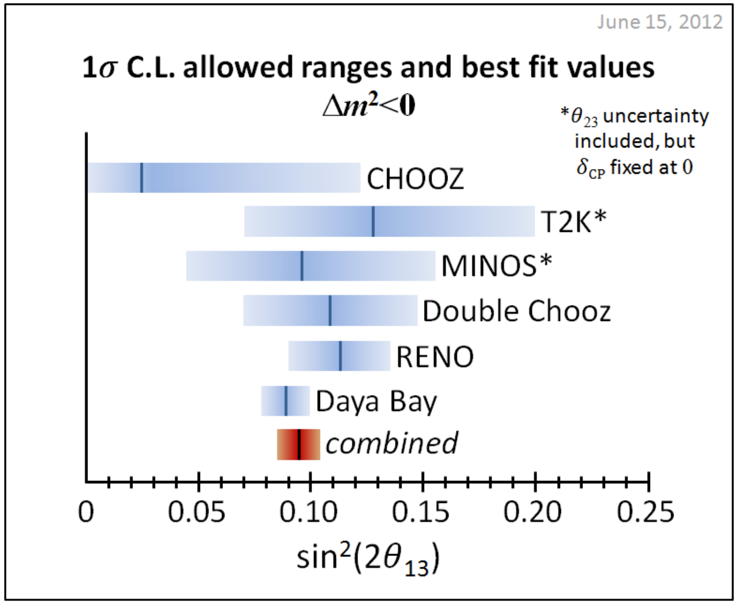

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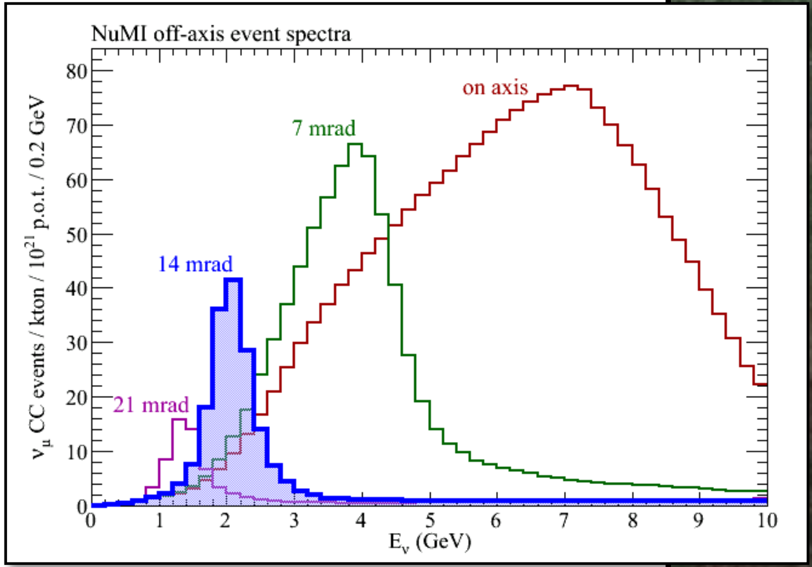
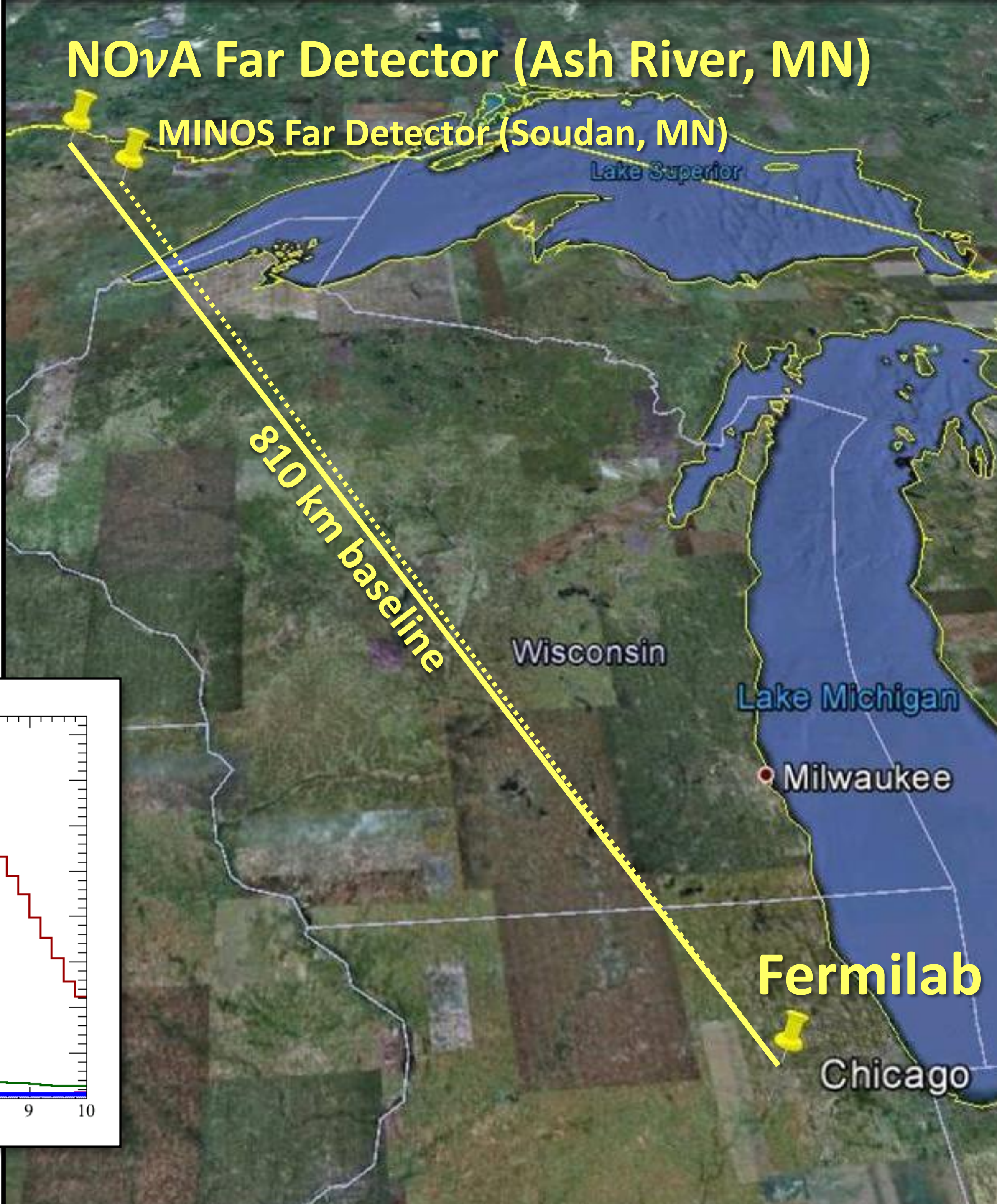
- **Future:** Will soon enough know θ_{13} and θ_{23} very well. Assume $\sin^2(2\theta_{23})=1$ and $\sin^2(2\theta_{13})=0.095$, and marginalize over δ:
  The MINOS data would prefer inverted hierarchy at 0.24σ
  (This is the approximate impact at the time of full T2K and NOνA exposures.)
- **Dream world:** Know θ_{13}, θ_{23}, and δ perfectly. If $\sin^2(2\theta_{23})=1$, $\sin^2(2\theta_{13})=0.095$, $\delta=0$:
  The MINOS data would prefer inverted hierarchy at 0.94σ
  (This is the approximate impact in the fullness of time.)

NOνA

As a segue from MINOS discussion, NOνA has:

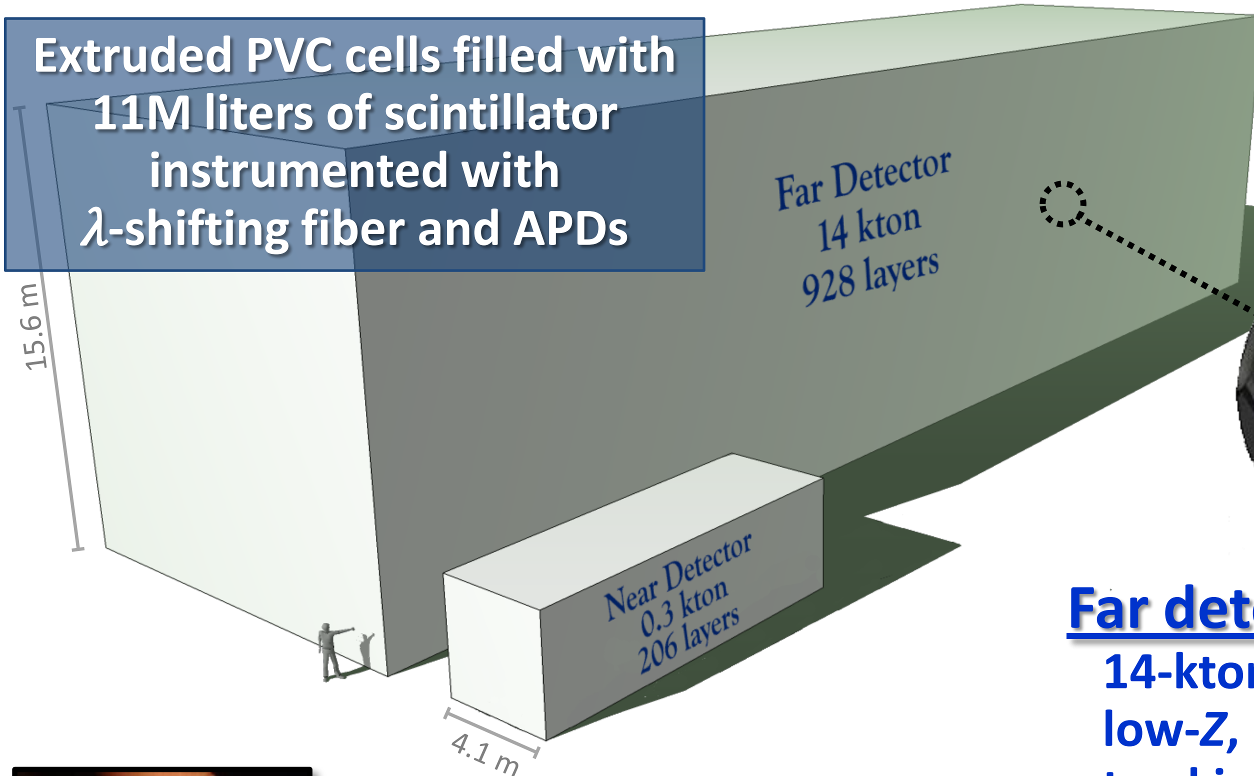
- **Similarly long baseline, NuMI to Ash River (810 km)**
- **Better-matched energy for oscillation max. (2 GeV)**
- **Narrow-band spectrum**
- **Larger exposure**
- **Much better detector for ν_e CC identification**



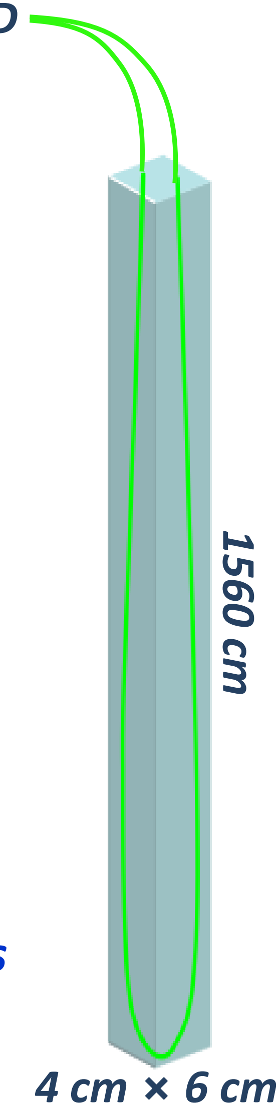


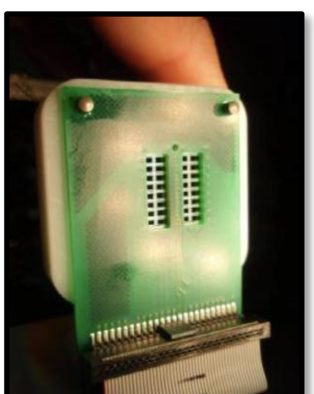
NOνA Detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs



A NOνA cell





32-pixel APD ←

Fiber pairs from 32 cells →

Far detector:

14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter

→ *360,000 channels*

→ *77% active by mass*

Near detector:

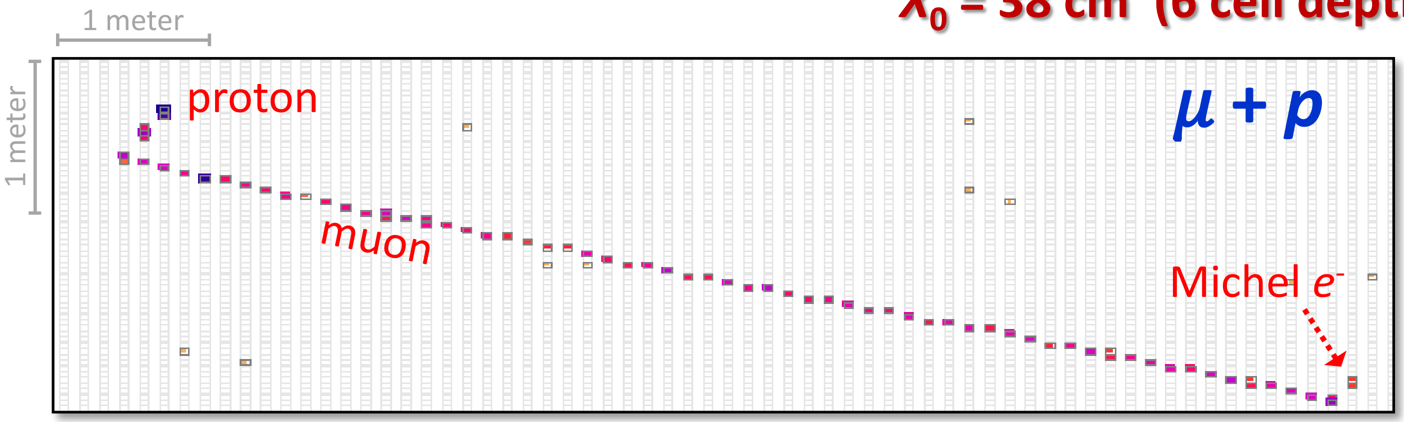
0.3-kton version of the same

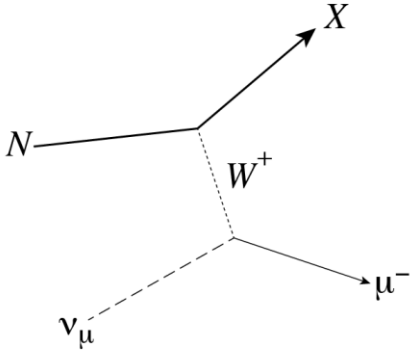
→ *18,000 channels*

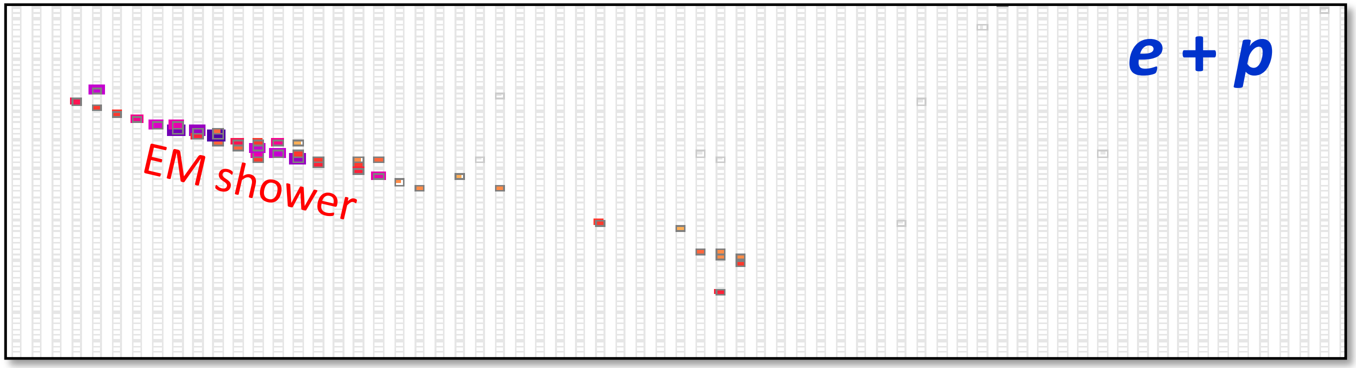
Events in NOvA

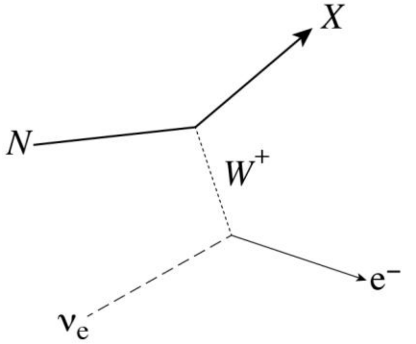
Superb spatial granularity for a detector of this scale

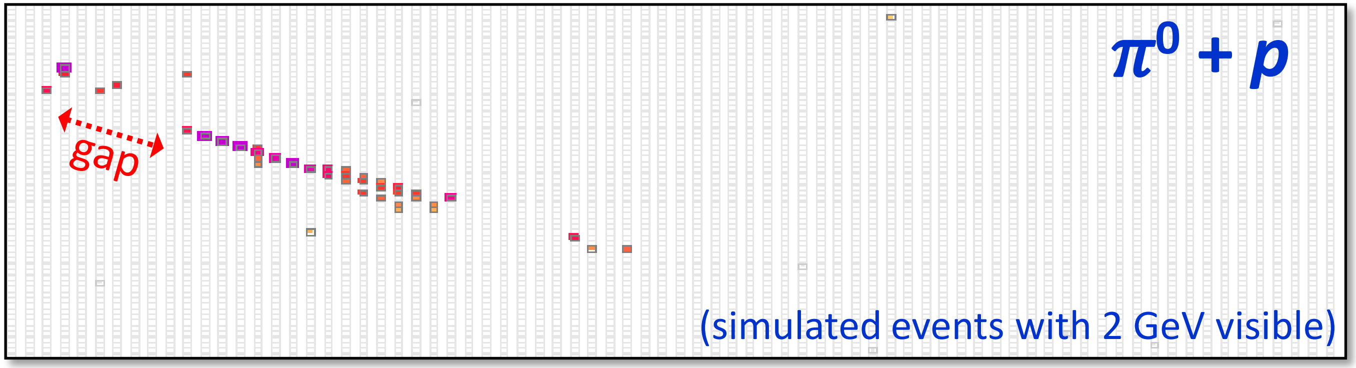
X_0 = 38 cm (6 cell depths, 10 cell widths)

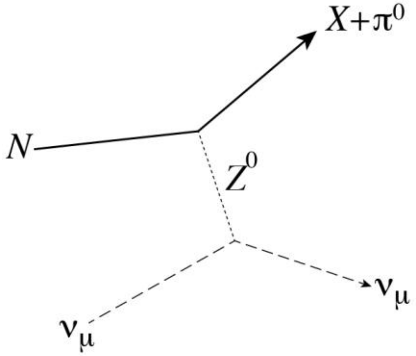






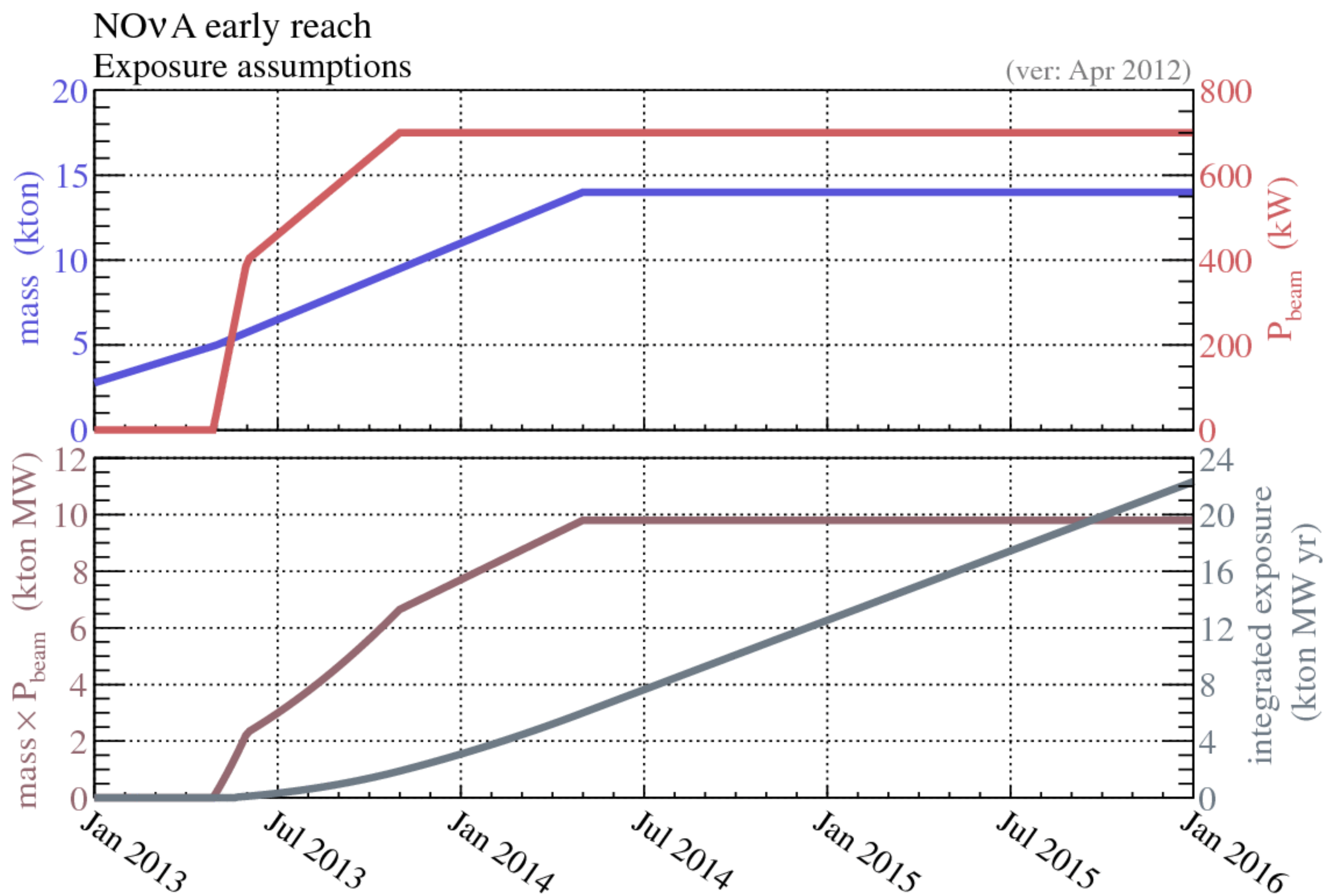






NOνA Exposure in Early Running

Evolution of detector mass and beam power…



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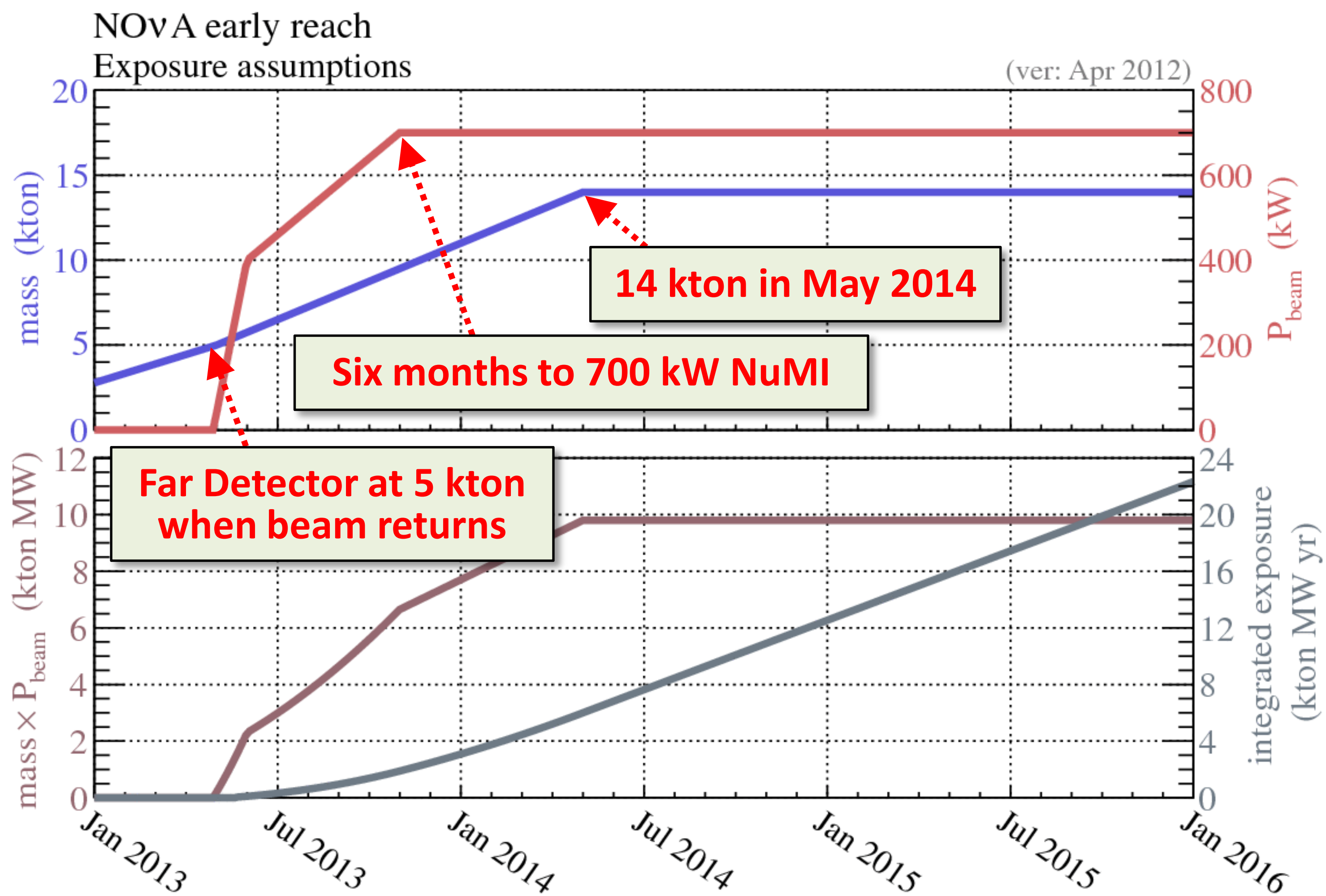
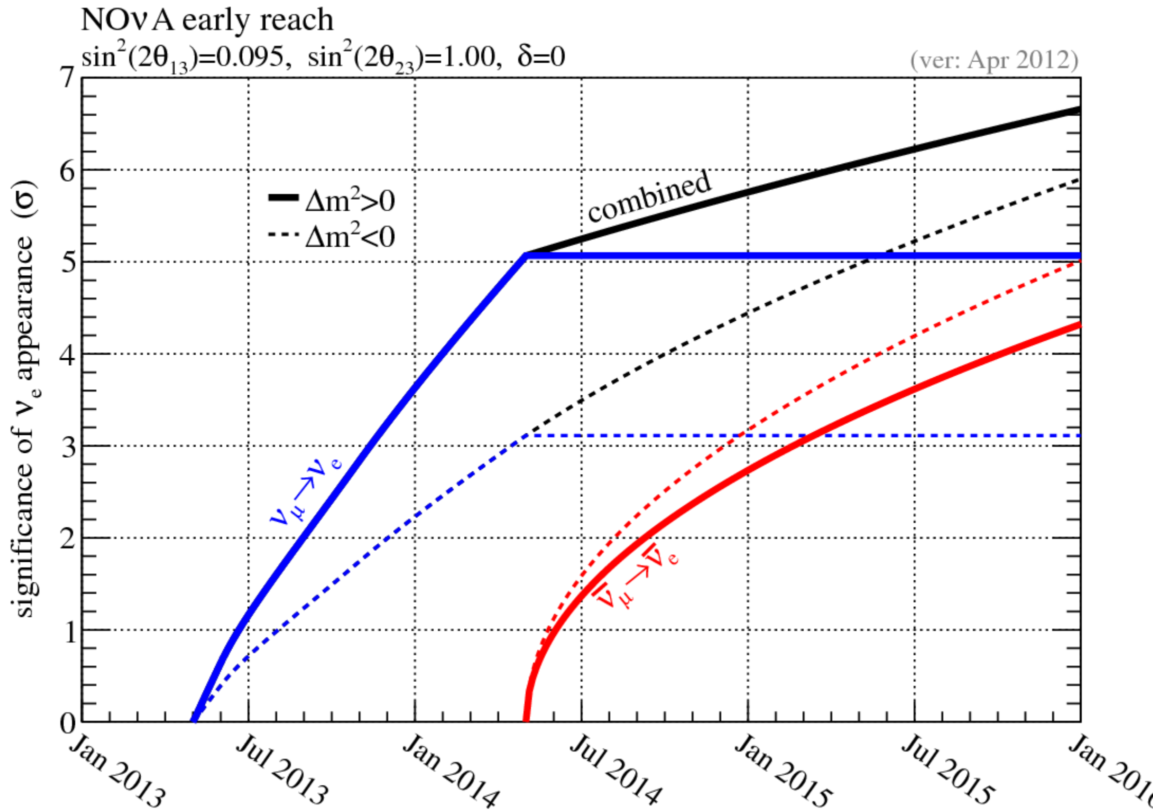


Early Reach

Will start with ν running

- **Can switch to $\bar{\nu}_\mu$ any time, optimizing the run plan based on our or others' results**
- **5σ observation of $\nu_\mu \to \nu_e$ in first year if NH**
  (even with partial detector and beam commissioning!)



And beyond…

Nominal run plan: 3 yr (ν) + 3 yr ($\bar{\nu}$) (with 6×10^{20} p.o.t./year)

- **Using NOνA's *earlier analysis methods*, but including new θ_{13} knowledge**
  ⇨ Taking $\sin^2(2\theta_{13}) = 0.095$
- **Representative event counts for $\nu_\mu \to \nu_e$ analysis** ⟶
  ⇨ *These depend greatly on the specific oscillation parameters*
- **Signal efficiency: 45%**
  NC fake rate: 0.1%

3 yr + 3 yr

beam = ν		$\bar{\nu}$
NC	19	10
ν_μ CC	5	<1
ν_e CC	8	5
tot. BG	32	15
$\nu_\mu \to \nu_e$	68	32

Measurement principle

NOνA will measure:

$P(\nu_\mu \to \nu_e)$ at 2 GeV

and

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ at 2 GeV

These depend *in different ways* on the CP phase δ and on sign(Δm^2) .

At right, these appearance probabilities are plotted as:

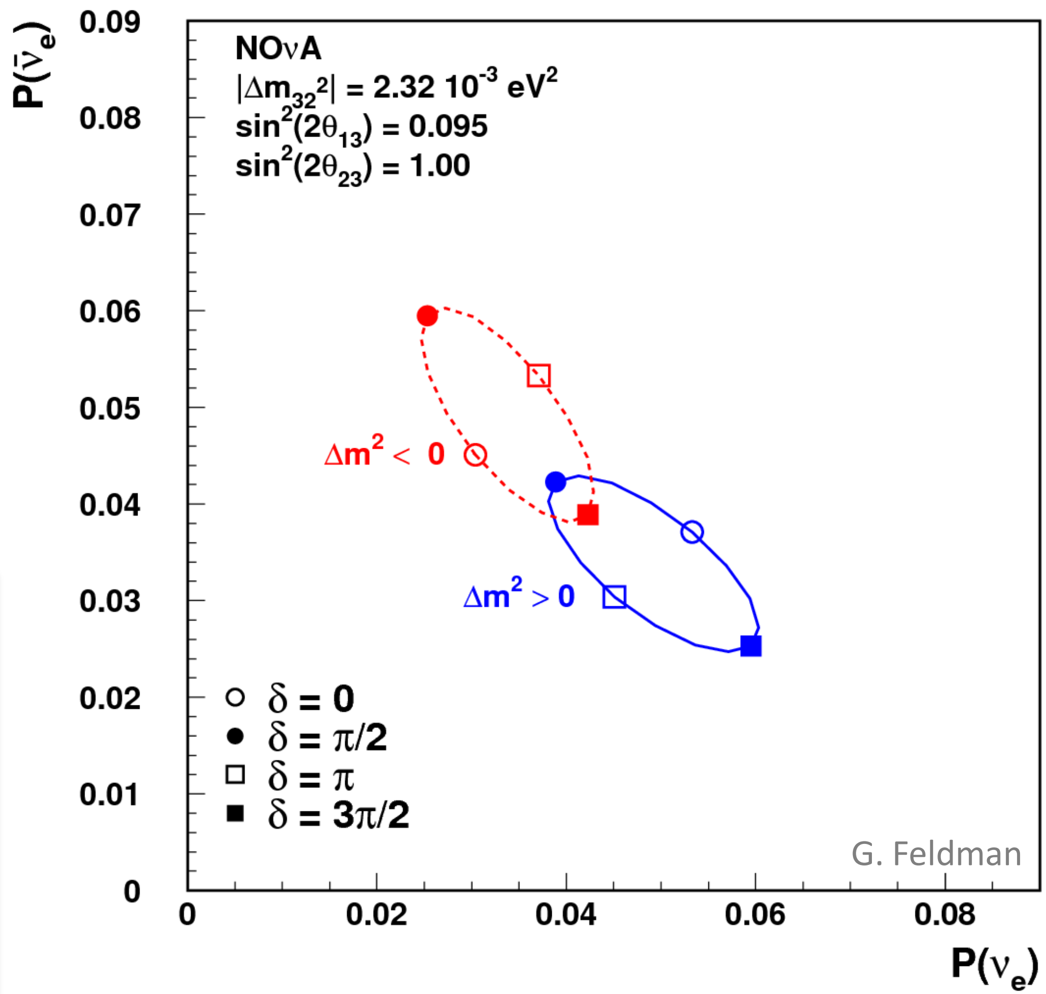
$P(\bar{\nu}_e)$ vs. $P(\nu_e)$

for all δ and both hierarchies

[*assuming:* $\sin^2(2\theta_{13})=0.095$, $\sin^2(2\theta_{23})=1$]

(This sketch ignores available spectral information.)

$P(\bar{\nu}_e)$ vs. $P(\nu_e)$ for $\sin^2(2\theta_{23}) = 1$



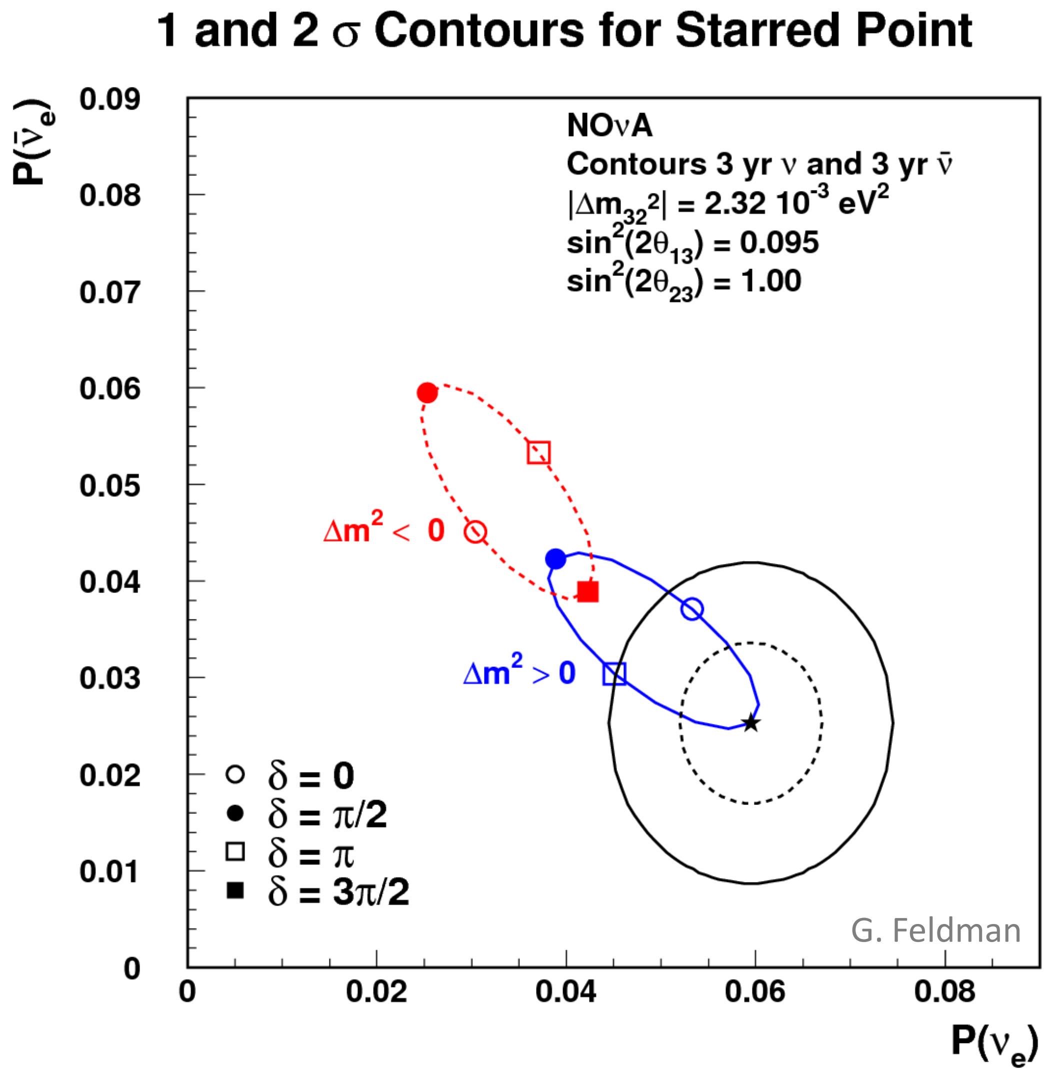
Measurement principle

Example NOνA result…

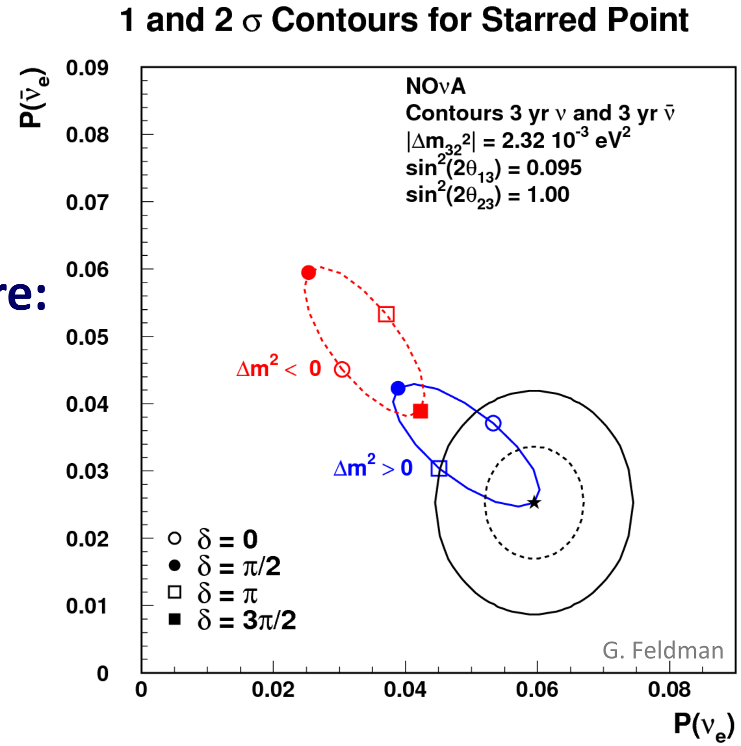
Our data will yield allowed regions in $P(\bar{\nu}_e)$ vs. $P(\nu_e)$ space

(3 yr + 3 yr possibility shown)

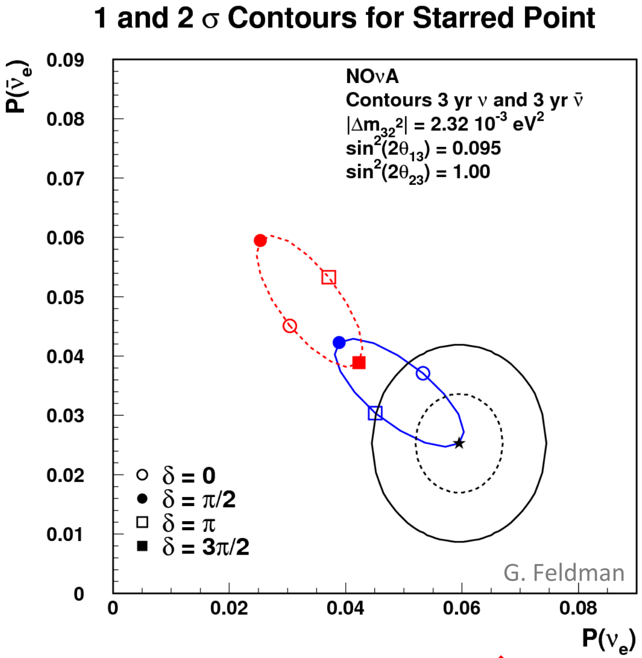
Here, all inverted hierarchy scenarios are excluded at >2σ.



Statistical interlude

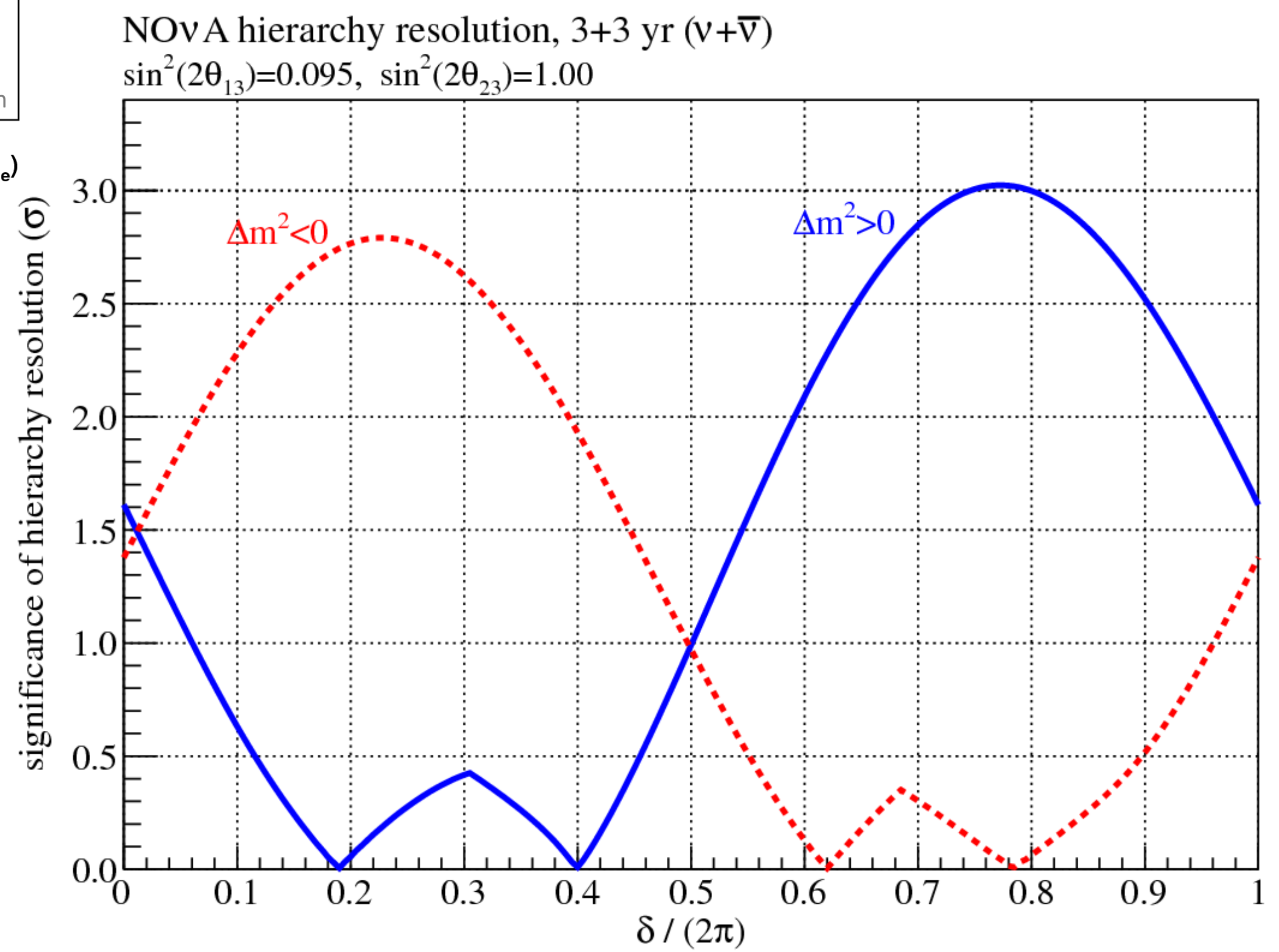


- **These plots are great for *qualitative* intuition about LBL sensitivities**
- **Good for *quantitative* intuition, too, but take care:**
  - The 2D space shown is not dense with possible answers; 2D contours aren't very interesting
  - So, 1D contours are drawn. Really, this just shows $\Delta\chi^2$ values between points, in "sigma" units
  - *For example:* the best inverted hierarchy point is apparently >2σ ($\Delta\chi^2$>4) worse than the expected best fit
- **Also: we're making measurements of discrete quantities (hierarchy; octant of θ_{23})**
  - An experiment with arbitrarily little hierarchy sensitivity will "exclude" the wrong hierarchy at 50% C.L. (not 0% C.L.) for any number of sensible constructions of frequentist intervals.
  - Someone instead talking about "number of sigma" based on $\Delta\chi^2$, would, in contrast, show 0σ (often interpreted at 0% C.L.)
- **While we're picking through the seedling sensitivity over the next couple of years, we'll have to pay more attention to statistics than perhaps we'd rather.**



NOνA hierarchy determination
…in a more general form

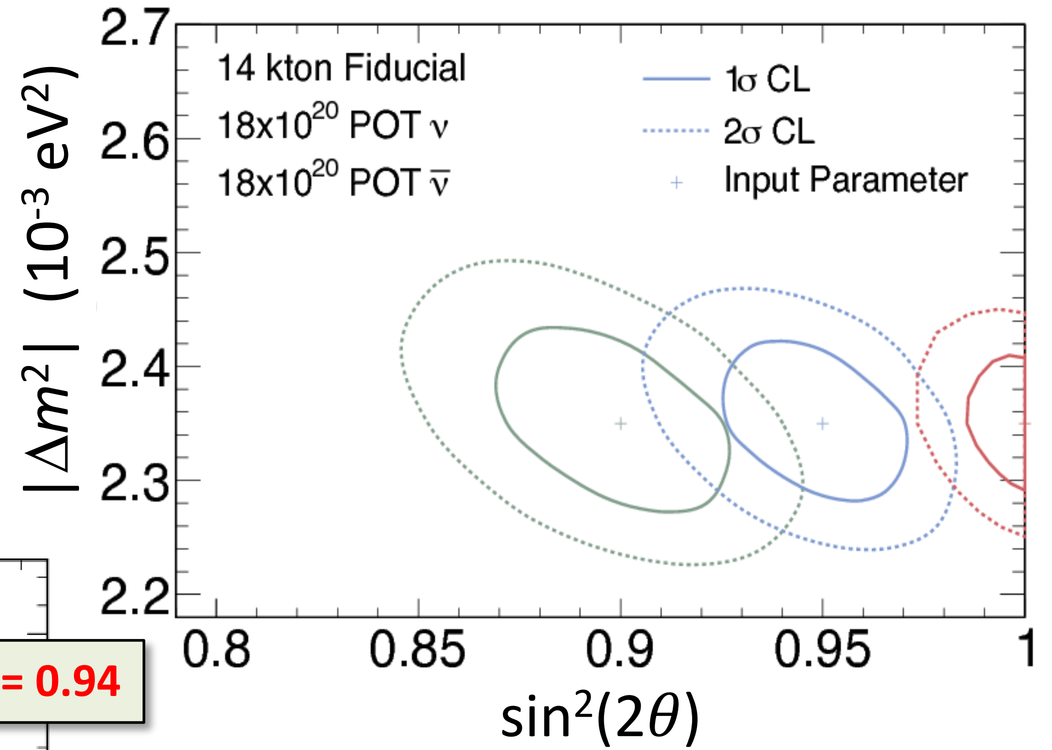
[still with: $\sin^2(2\theta_{13})$=0.095, $\sin^2(2\theta_{23})$=1]

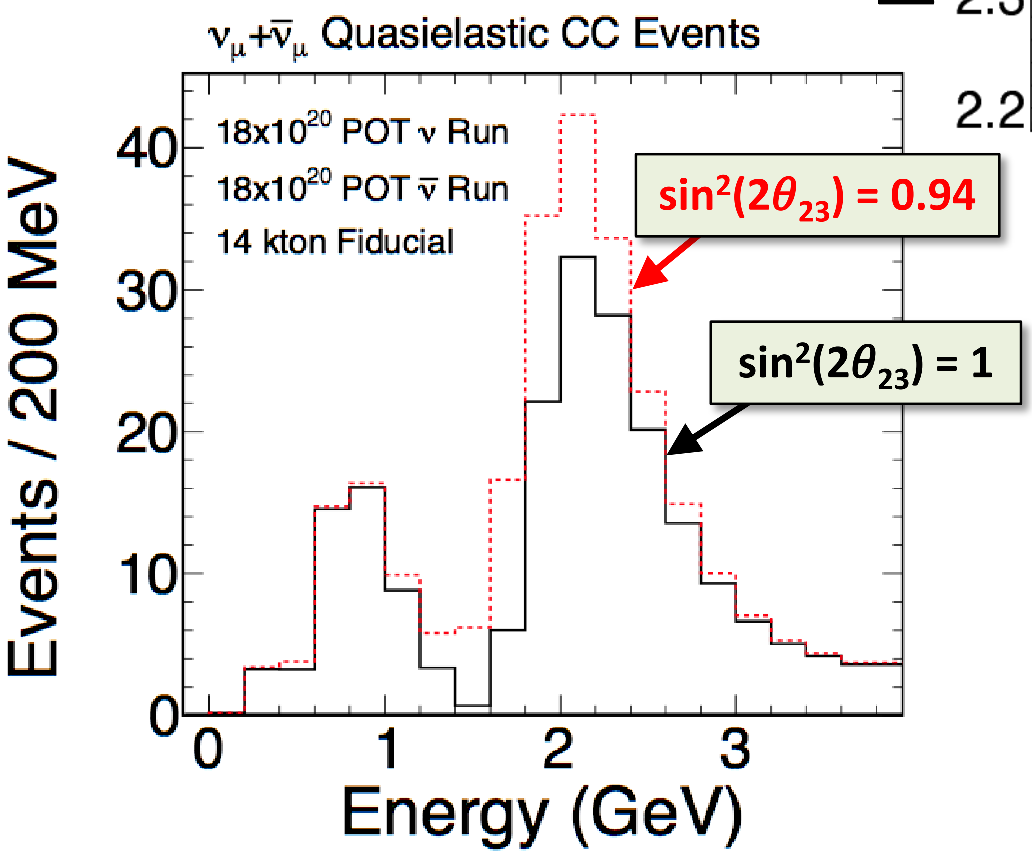


(will combine with T2K later)

$\sin^2(2\theta_{23}) \neq 1$?

Example NOνA contours for three test points →





4% energy resolution for the QE sample.

Inclusive ν_μ CC sample should be background-free

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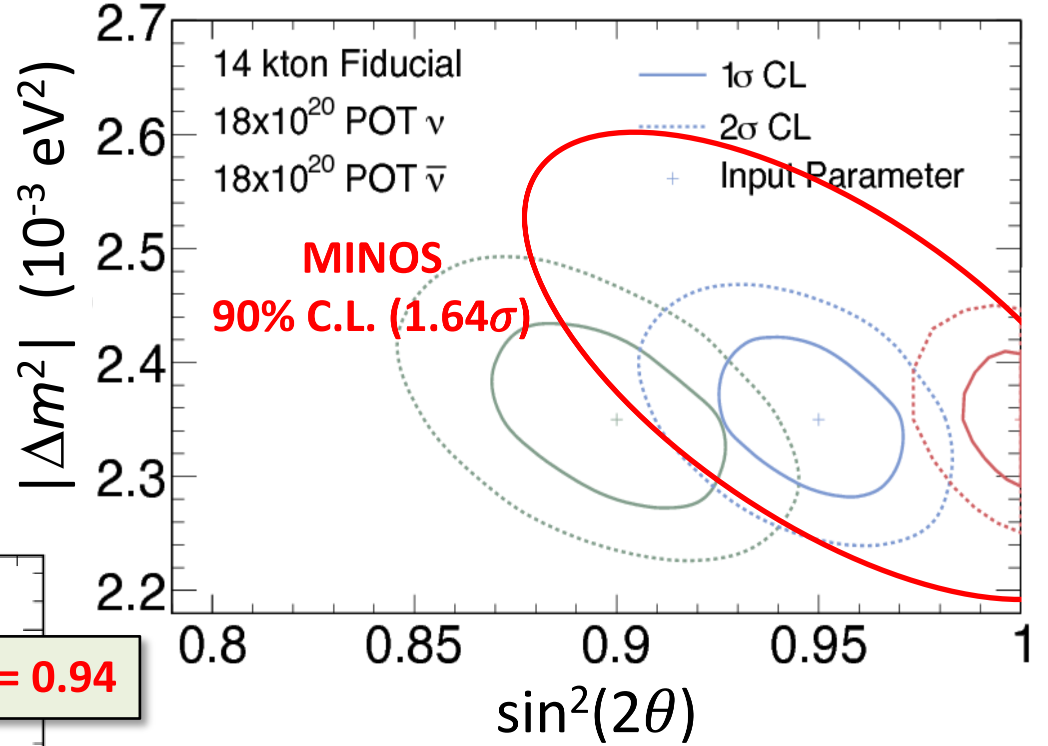

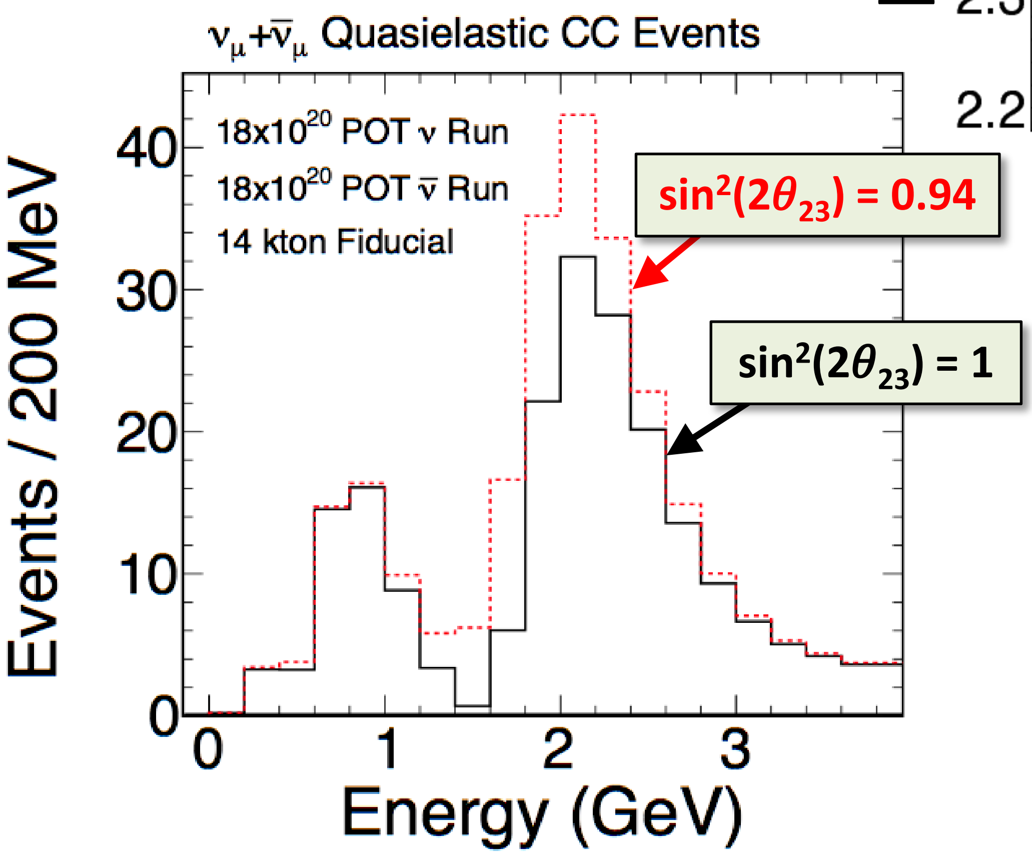

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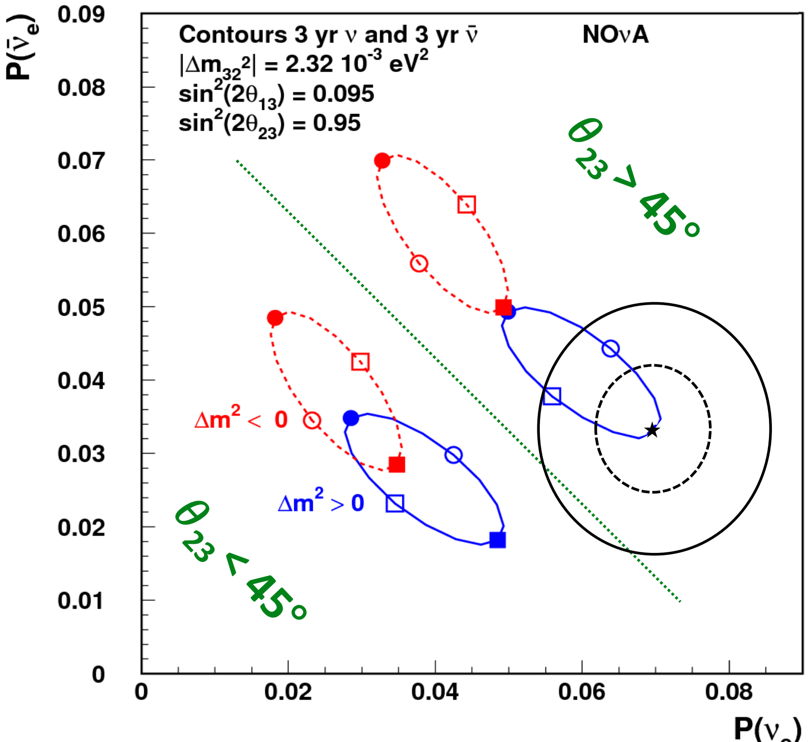
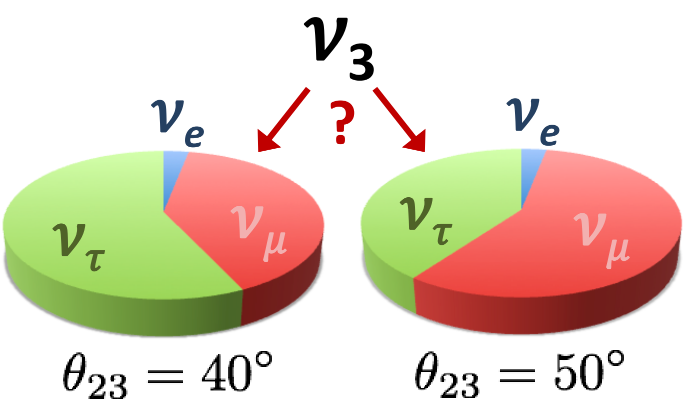
$P(\nu_e) \propto \sin^2(\theta_{23})\sin^2(2\theta_{13})$

⇨ *θ_{23} octant sensitivity*

Expected NOνA contours for one example scenario at 3 yr + 3 yr





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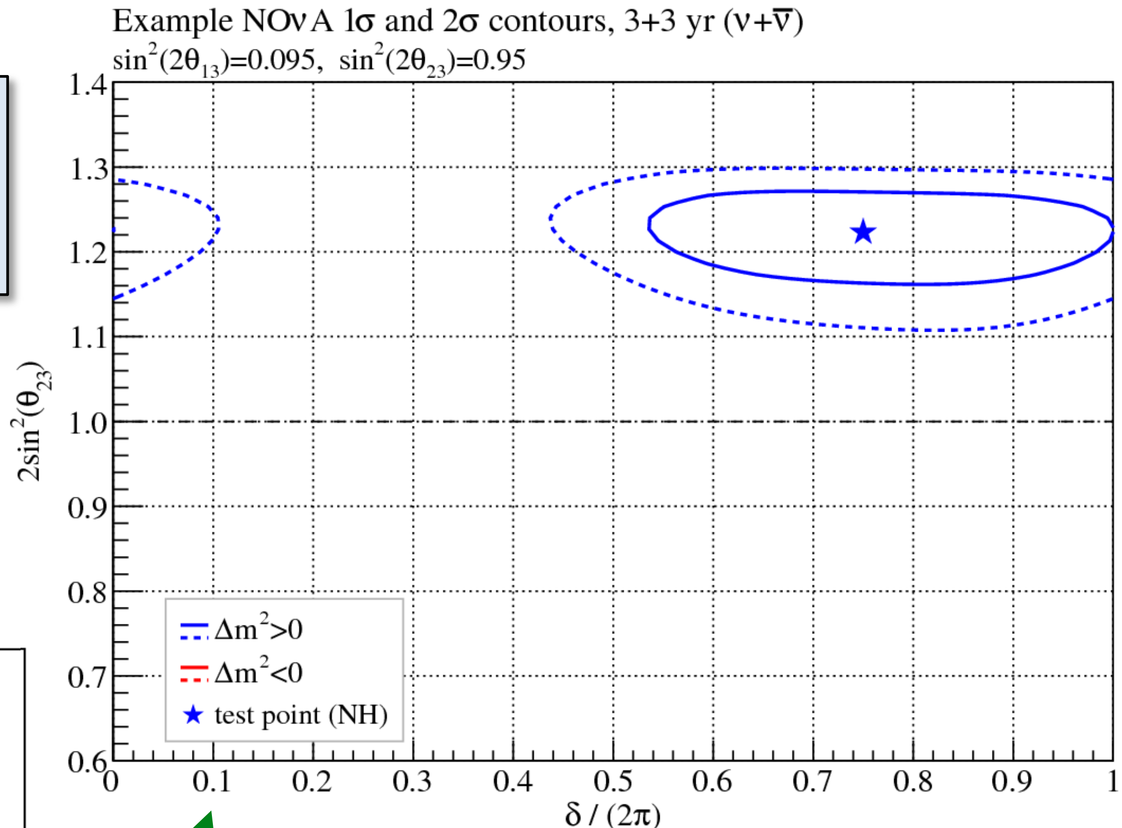

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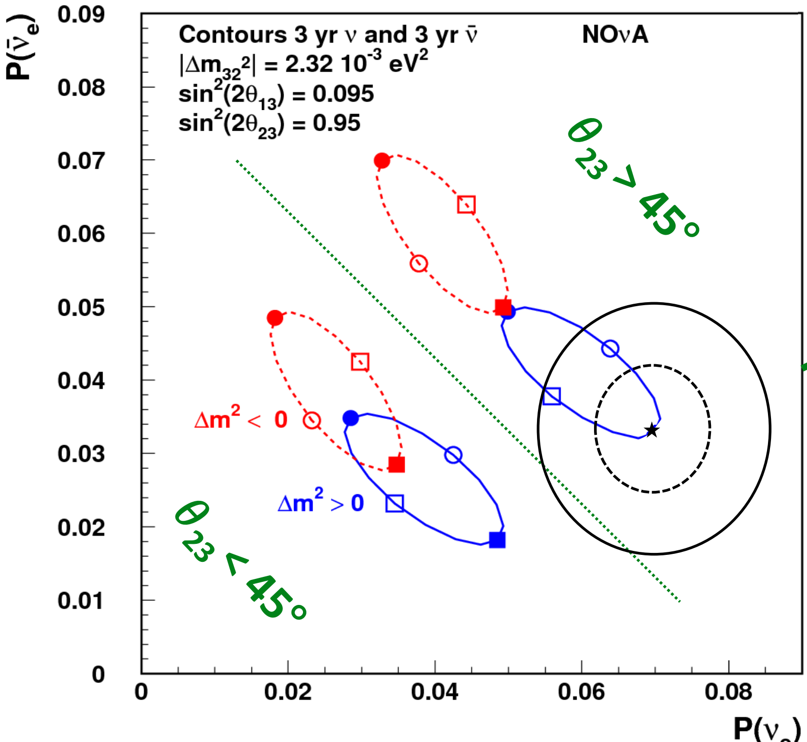
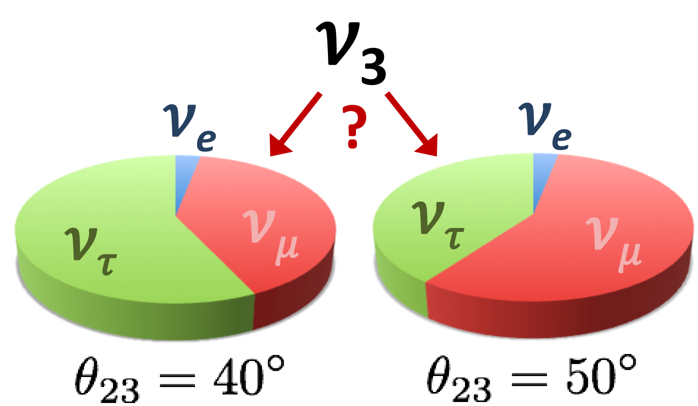


Simultaneous <u>hierarchy</u>, <u>CP phase</u>, and <u>θ_{23} octant</u> information from NOνA



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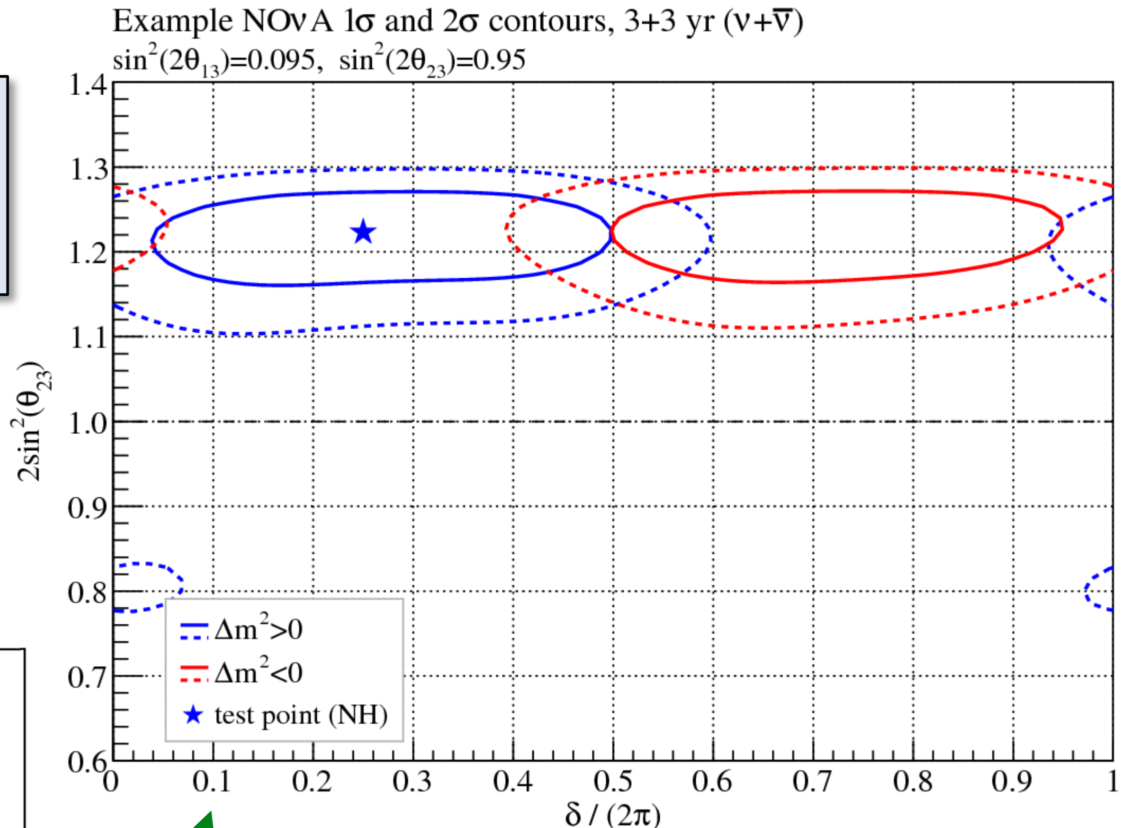
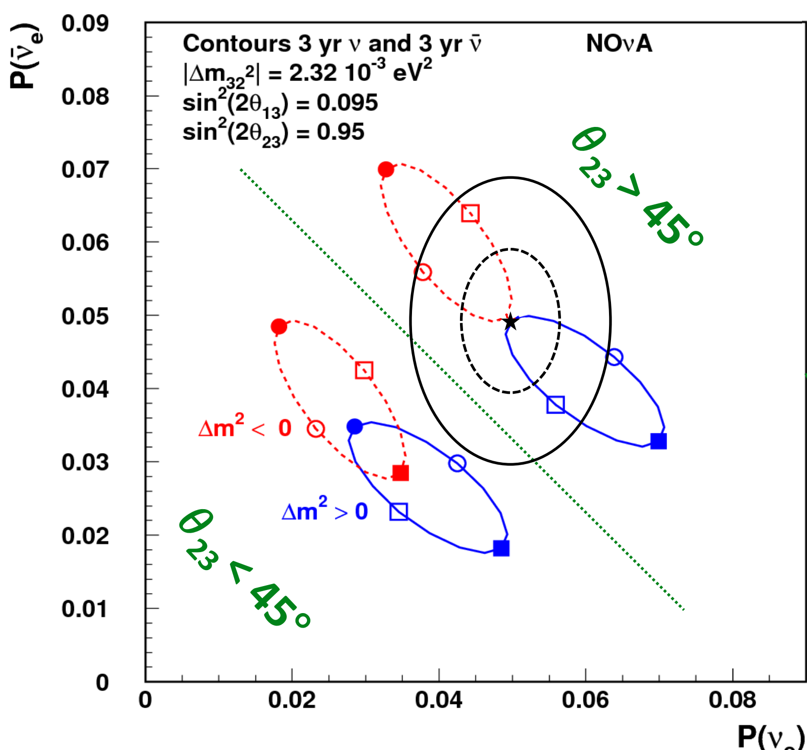
$P(\nu_e) \propto \sin^2(\theta_{23})\sin^2(2\theta_{13})$

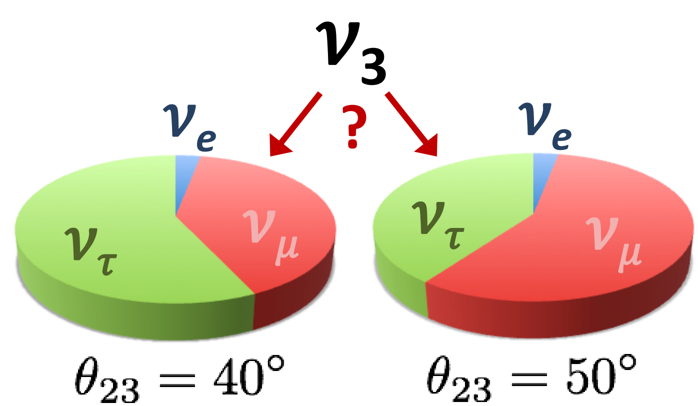
$\Rightarrow$ ***θ_{23} octant sensitivity***



Expected NOνA contours for one example scenario at 3 yr + 3 yr



In "degenerate" cases, hierarchy and δ information is coupled. θ_{23} octant information is not.



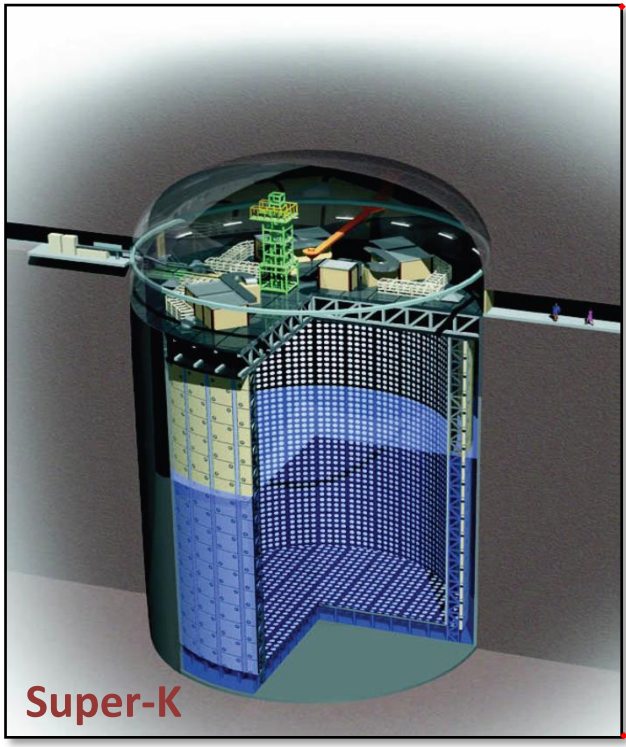
Ryan Patterson, Caltech

General comments on NOνA reach

- **MINOS experience and improved data on cross sections since NOνA numbers were determined suggest that π^0 backgrounds are likely over-estimated, cross-section-wise.**
  - In MINOS, the Near Detector yielded 15%–40% fewer ν_e-candidate NC events than the simulation predicted. (Note: this is well within *a priori* uncertainties.)
- **New PID approaches, energy fitting, discriminant fitting possible**
- **Non-QE and non-contained ν_μ CC samples unexplored (significant number of events, but each event not as well characterized)**
- **First round analyses will likely remain relatively simple, but there are several years ahead for realizing potential improvements.**
  - Historically, these sorts of things have been worth an addition 30% or so in reduction of errors…
- **This is all my own personal speculation in the spirit of PXPS discussion, not official claims of any sort.**

T2K

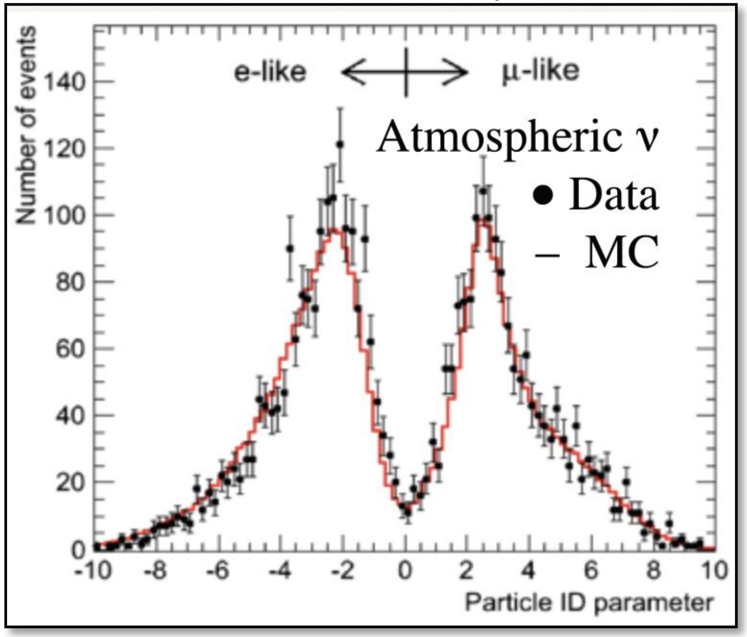
- Tokai to Kamioka (295 km)
- New neutrino beam from J-PARC
- Existing far detector: Super-K
  - *well understood detector*
  - *existing analysis tools*
- INGRID and ND280 near detectors
- A T2K/J-PARC status talk follow this

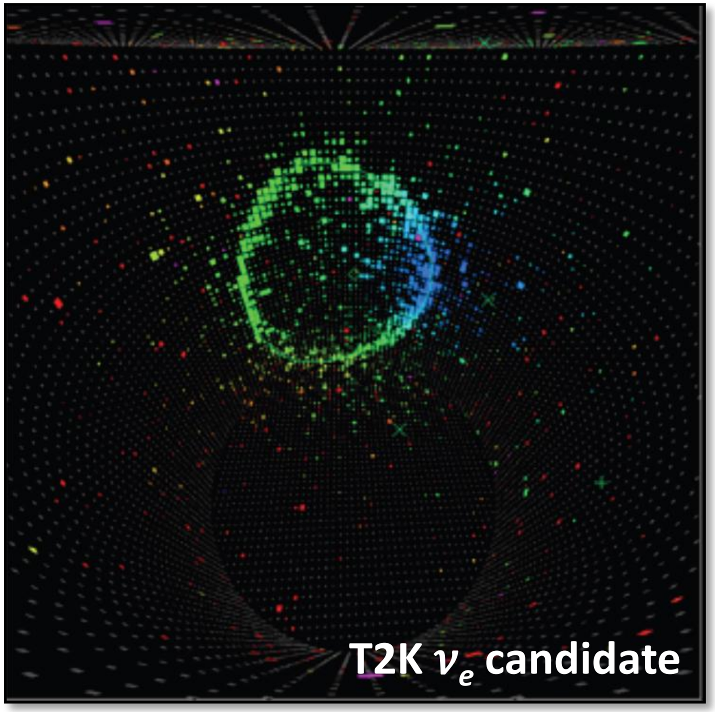


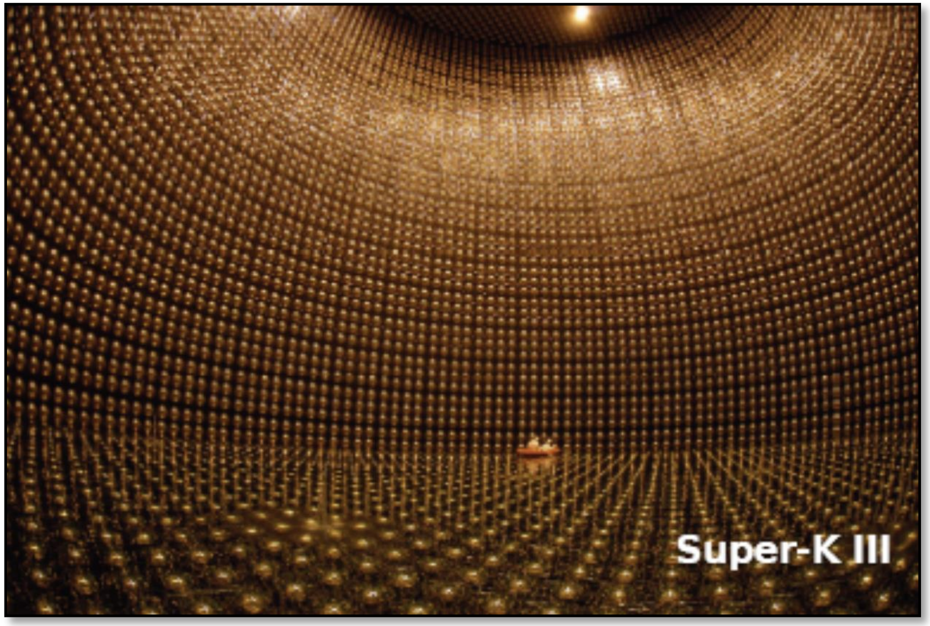
Super-K events

- **Long history of ~GeV events in Super-K**
  - *- Super-K atmospheric data* ⟶
- ***Major plus:* quick, robust analysis from T2K**
- **Can be hard to change or improve long-standing techniques…**
  - *…but not impossible!*

from Super-K collab.



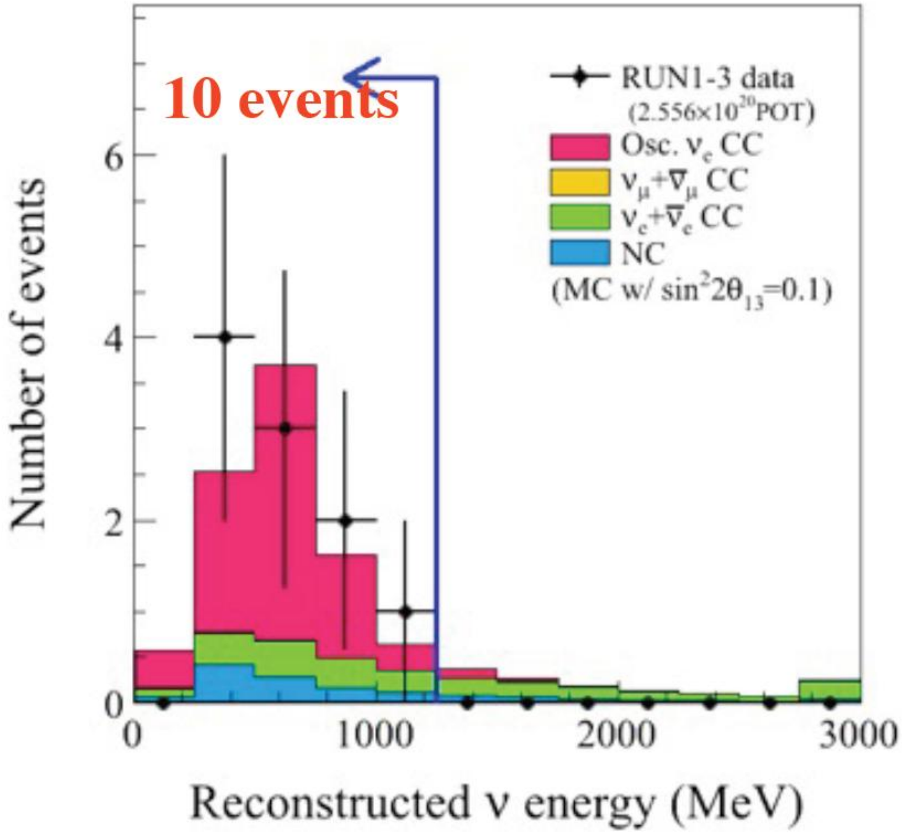




Latest T2K ν_e appearance result

- **From Neutrino 2012** *(T. Nakaya)*
- **3.2σ evidence of ν_e appearance, with 2.56×10^{20} p.o.t.**
  (When beam gets to full power, this exposure take only 2 months!)

10 events in signal region



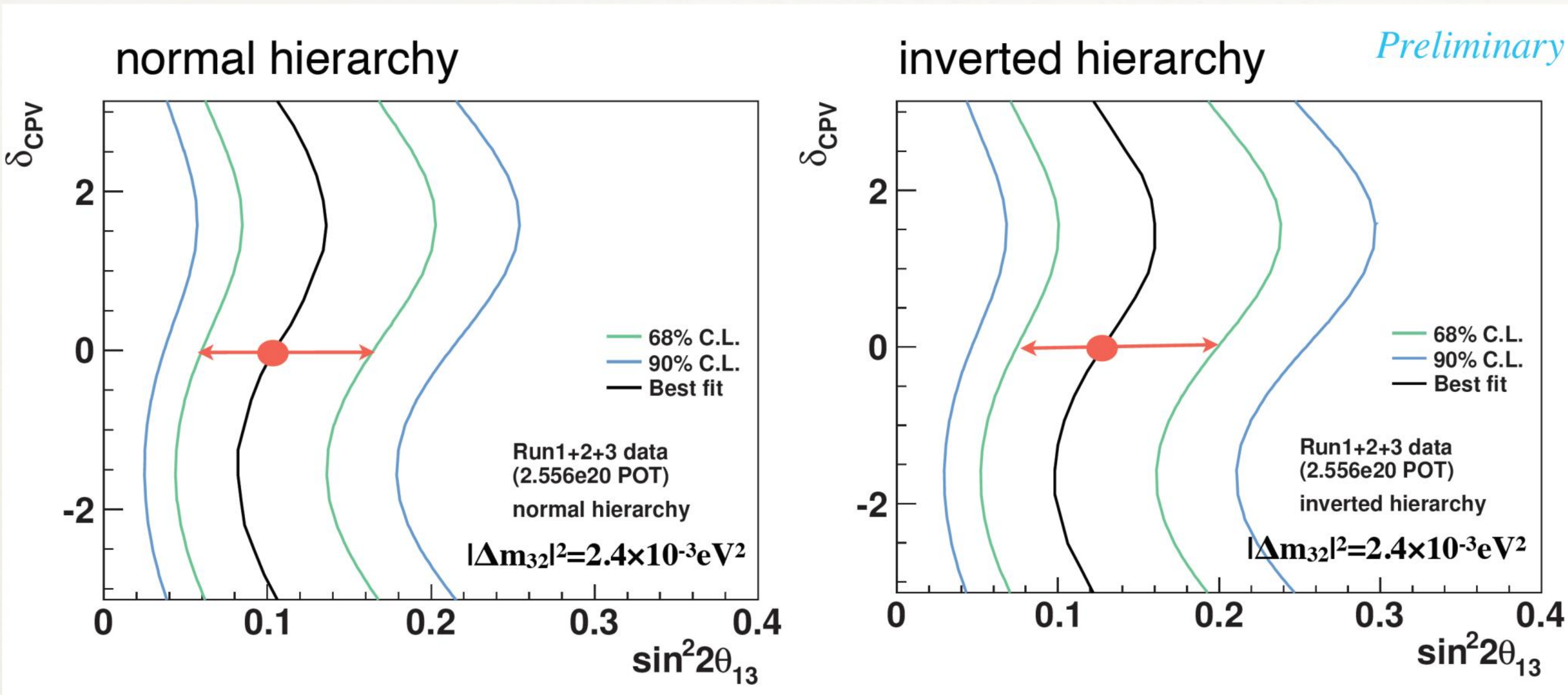
Representative predictions, errors

	$\sin^2 2\theta_{13}=0.1$
Total	**9.07±0.93**
ν_e signal	6.60
ν_e background (beam org.)	1.32
ν_μ background (~NCπ^0)	1.02
anti-ν background	0.13

	$\sin^2 2\theta_{13}=0.1$
Flux+Xsec in T2K fit	5.7%
Xsec (from other exp.)	7.5%
SK + FSI	3.9%
Total	**10.3%**

Latest T2K ν_e appearance result

T. Nakaya, for T2K



$\sin^2 2\theta_{13} = 0.104\,^{+0.060}_{-0.045}$ @ $\delta_{CP} = 0$

$\sin^2 2\theta_{13} = 0.128\,^{+0.070}_{-0.055}$ @ $\delta_{CP} = 0$

Looking beyond this result

- **Figures that follow are not from T2K but rather my own calculations**
  - *I look forward to analogous information coming out of T2K for comparison*
- **Assuming the exposure profile official from T2K as of the LBNE re-configuration workshop** *(taken from Y.-K. Kim's intro talk)* →
- **Normalizing to event counts just shown in T2K prediction table**
- **Assuming systematic errors will go down (10.3%→8%, arbitrarily), and performing counting expt.**
- **For anti-ν running, assuming:**
  - *same selection efficiencies*
  - *same energy spectrum*
  - *3.8x reduction in rate*
    (15% from flux, the rest from cross sections)

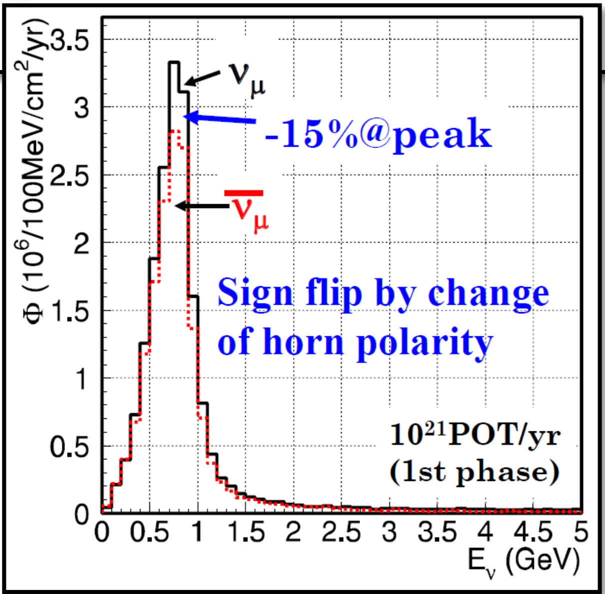
Period	Integ. No. of Proton on Target	Beam Power (kW)	
-Jun.2012	3.1E+20	170	
-Jun.2013	7.8E+20	200	
-Jun.2014	1.2E+21	250	*2
-Jun.2015	1.8E+21	250	
-Jun.2016	2.5E+21	300	
-Jun.2017	3.2E+21	300	
-Jun.2018	3.9E+21	300	
-Jun.2019	5.5E+21	700	*1
-Jun.2020	7.1E+21	700	
-Jun.2021	8.8E+21	700	

*1 Completion time of MR upgrade (assumed to be 2018) is suject to change, depending on economical situation, readiness and so on.

*2 LINAC upgrade completed

* Beam Energy 30GeV

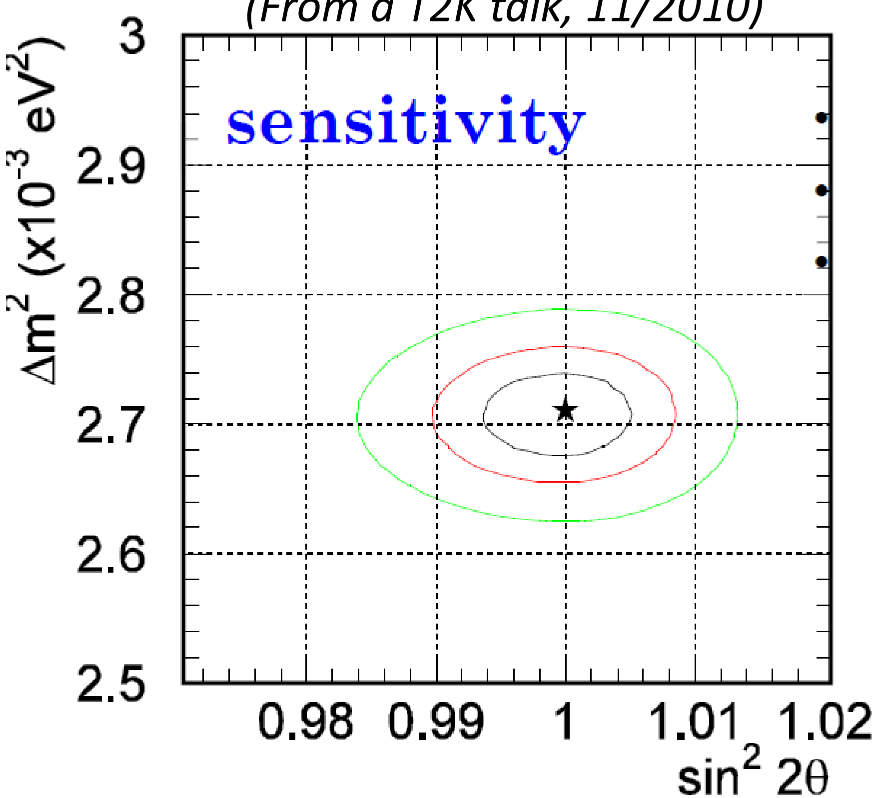
Antineutrino flux from an old T2K talk (at 2° off axis)



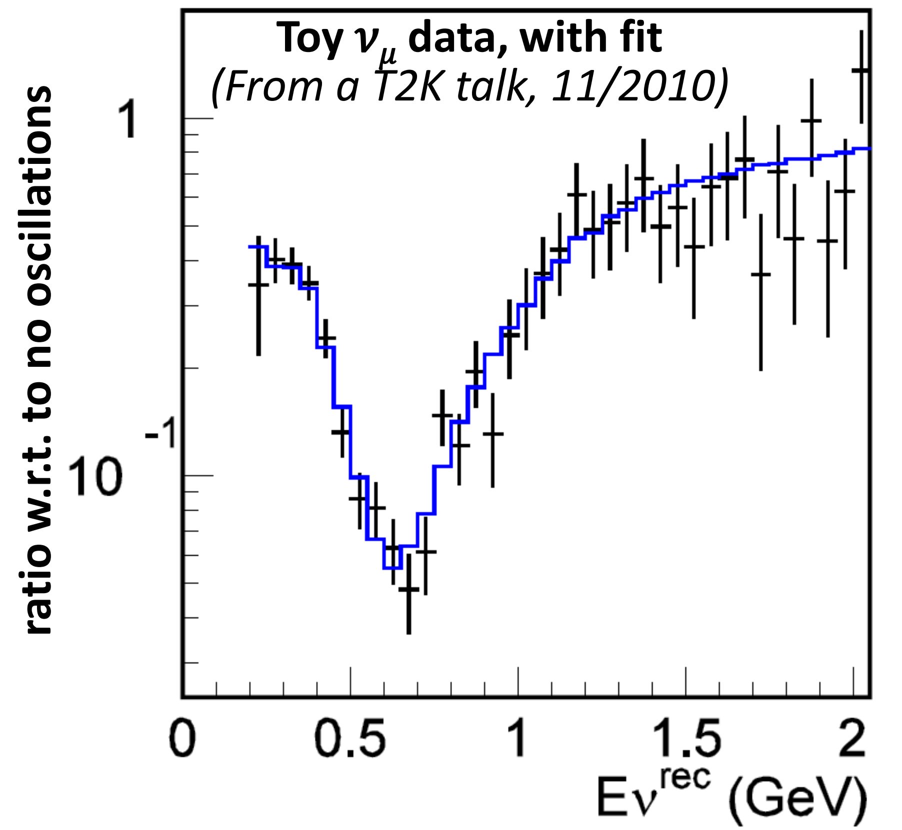
For ν_μ disappearance

- **Assuming ν_μ CC disappearance sensitivity to $\sin^2(2\theta_{23})$ is equal to NOνA**

Atmos. parameter sensitivity at full 5-yr, 750 kW (?) exposure with no systematic errors
(From a T2K talk, 11/2010)



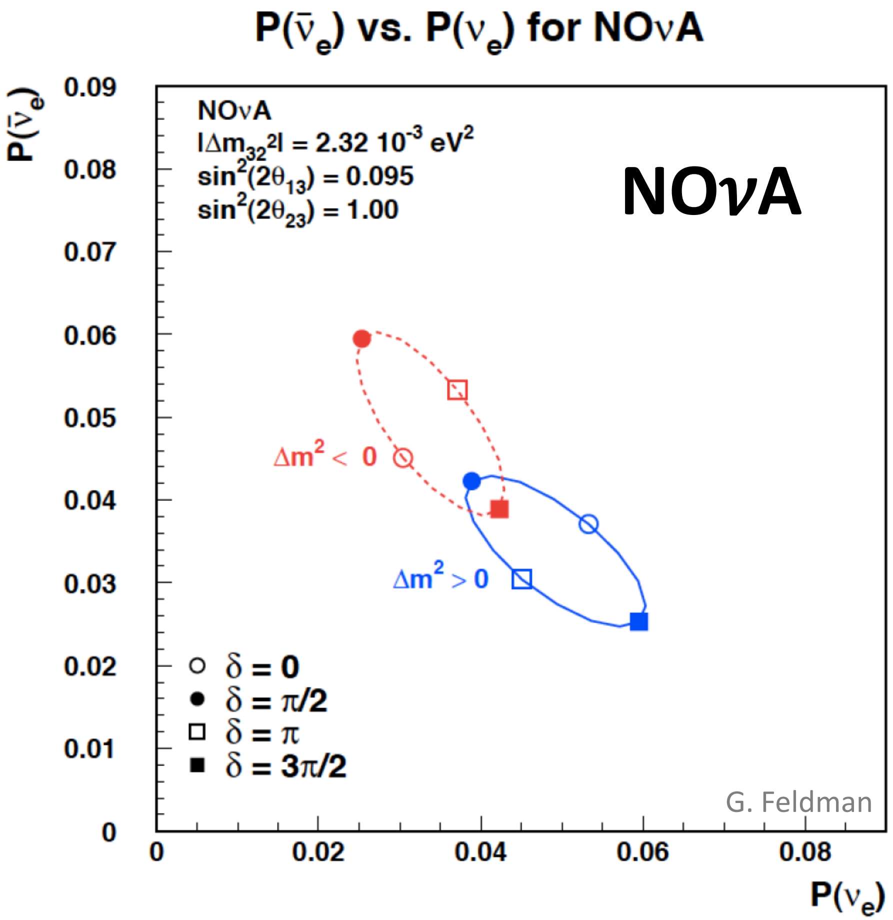
Toy ν_μ data, with fit
(From a T2K talk, 11/2010)

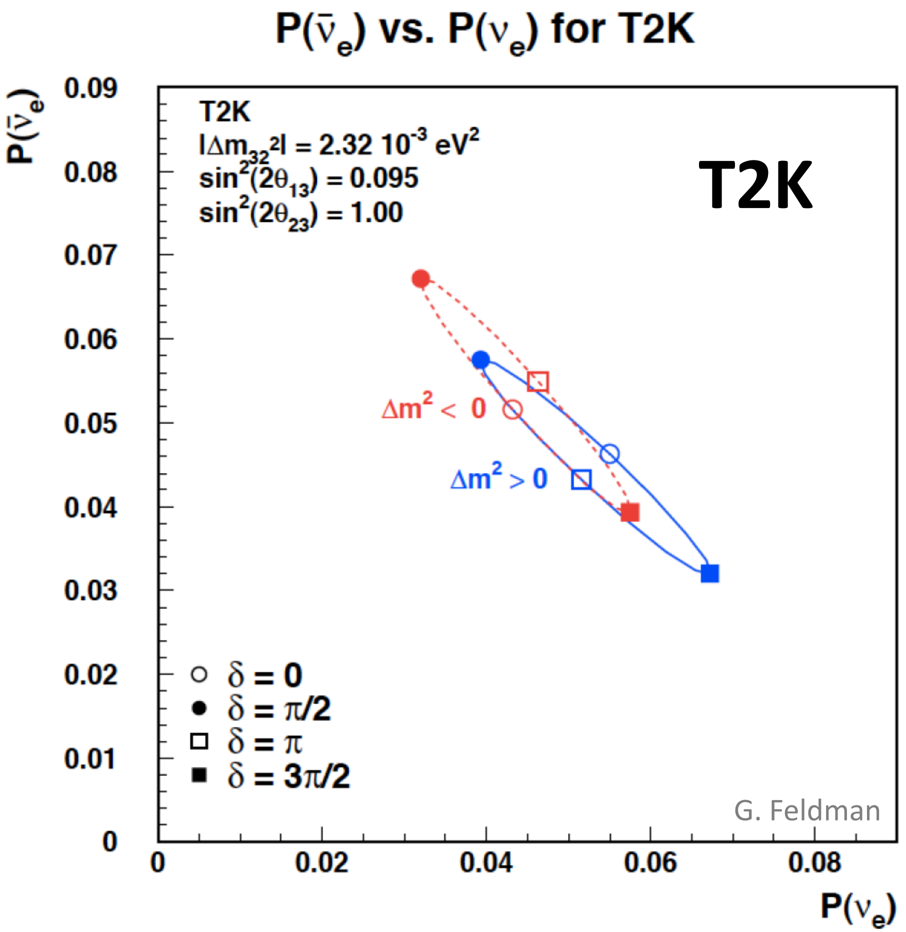


- **Systematic errors take $\sin^2(2\theta_{23})$ error to <u>1%</u>** *(from same T. Nakaya talk)*
- **Reduction of exposure to forecast levels for 2019 plus possible antineutrino running would reduce this a bit further, but ignoring these losses (1%→1.5%)**

Qualitative expectations?

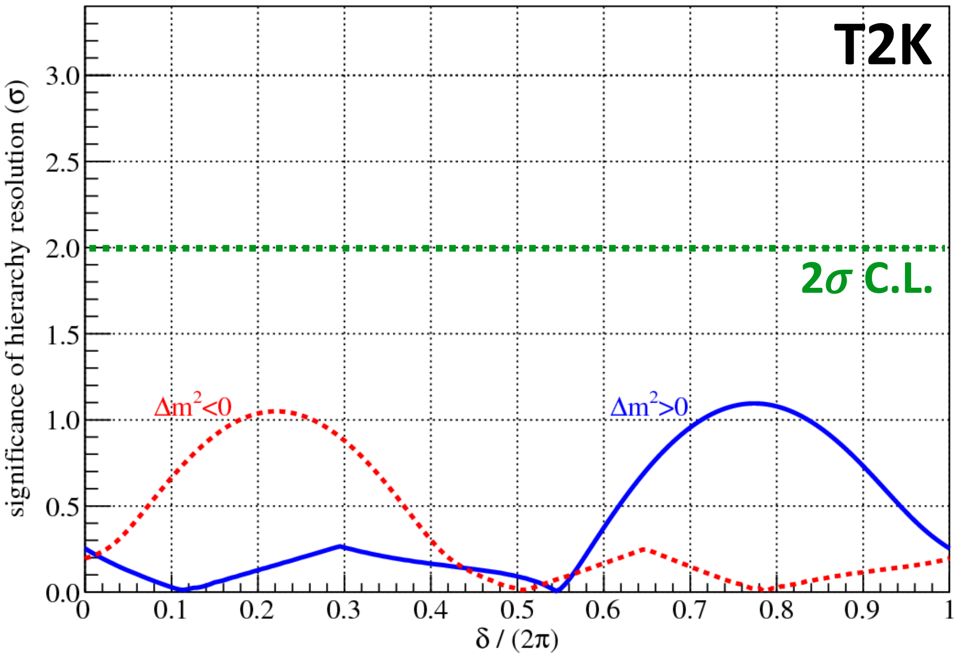
- **hierarchy sensitivity** ⇔ **separation of ellipses**
- **CPv sensitivity** ⇔ **δ=0 and $\delta=\pi$ points displaced from other points**
- *(Note: expected NOνA and T2K errors on these probabilities are similar, 10%–30%)*

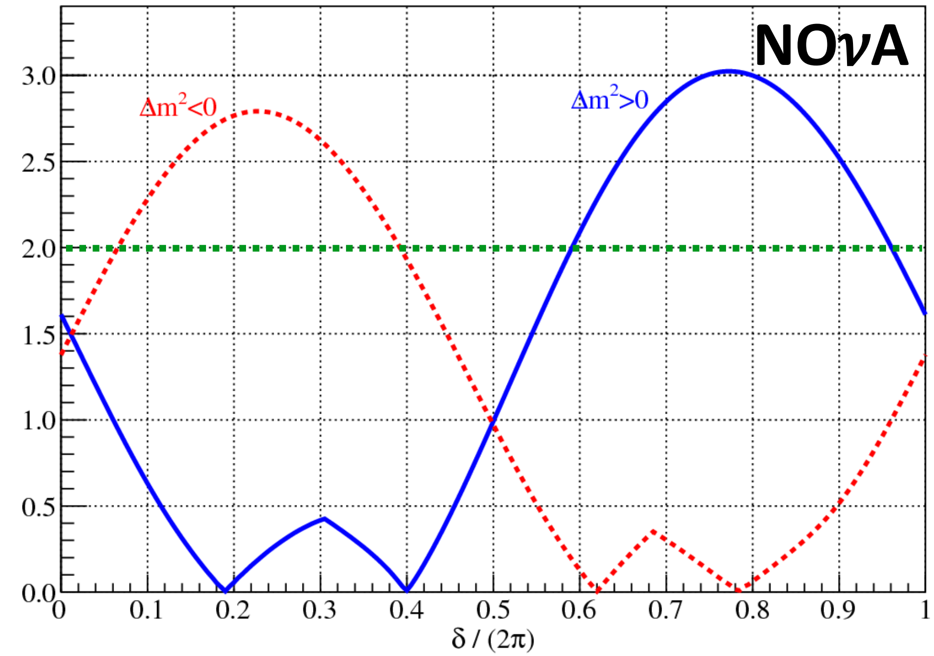




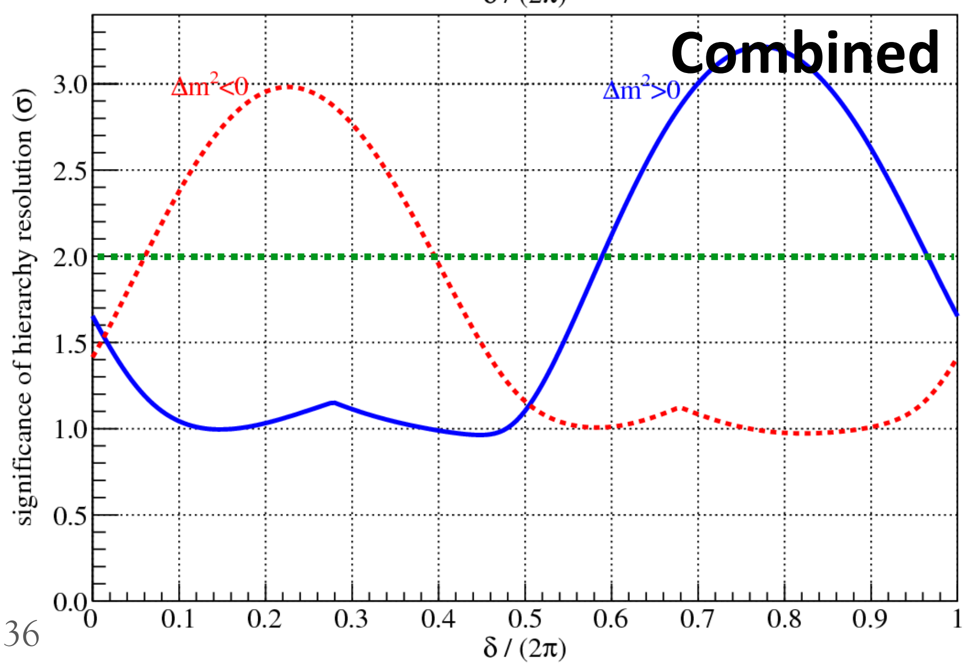
Hierarchy resolution at the end of 2019.
Even split of ν and $\overline{\nu}$ running at both expts.

For test scenario of $\sin^2(2\theta_{13})=0.095$, $\sin^2(2\theta_{23})=1$



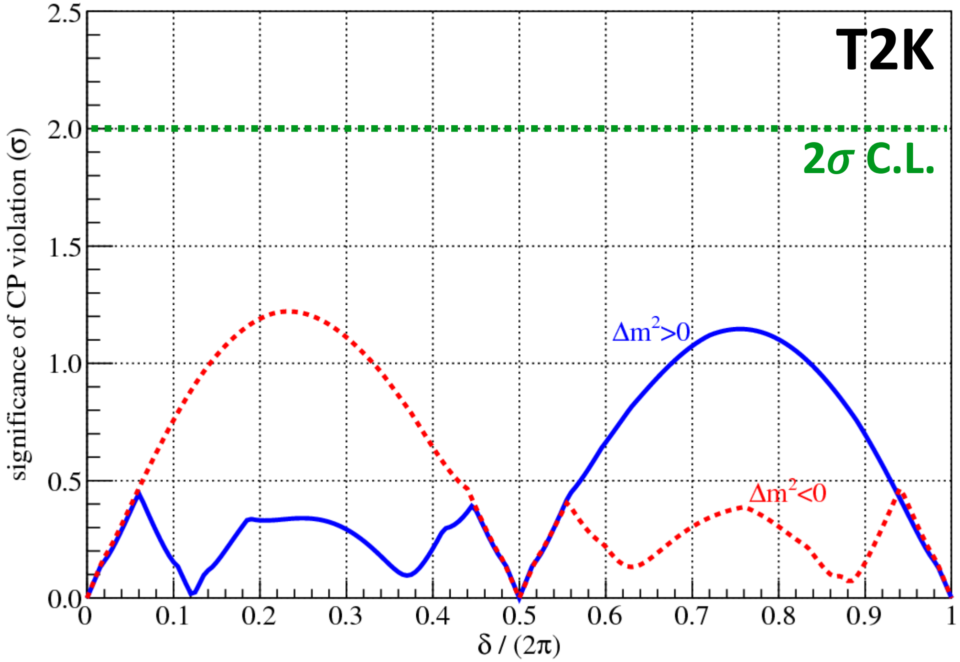


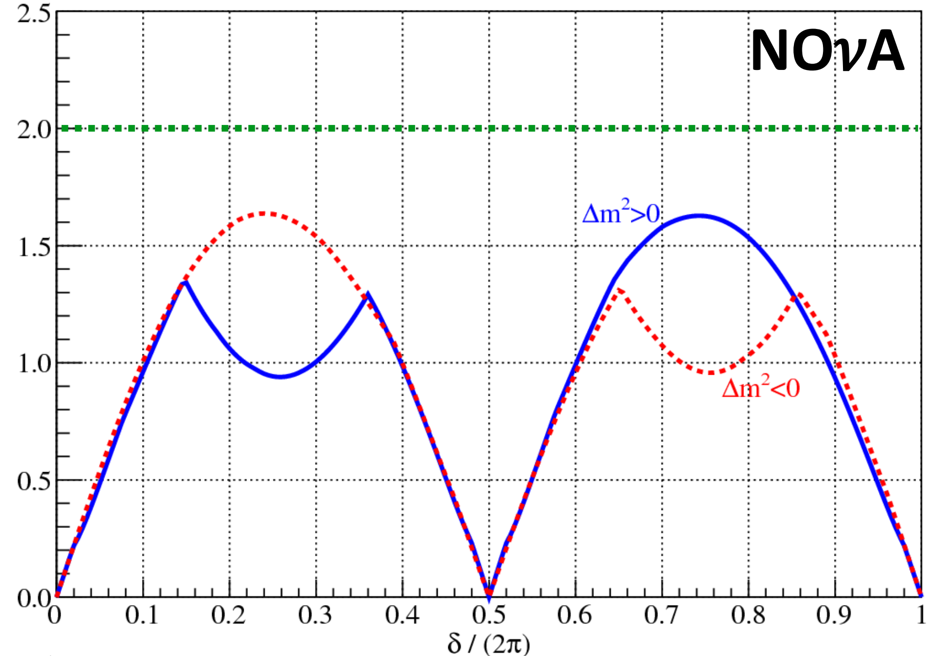
- **2σ C.L. (~95% C.L.) marked in green**
- **T2K baseline** too short for hierarchy
- **<u>NOνA alone:</u>** 37% of δ range covered
- **<u>NOνA+T2K:</u>** 38% of δ range covered
- *But:* note that the **combination is greater than the sum of its parts** in the "degenerate" region (reaching a modest 1σ everywhere)



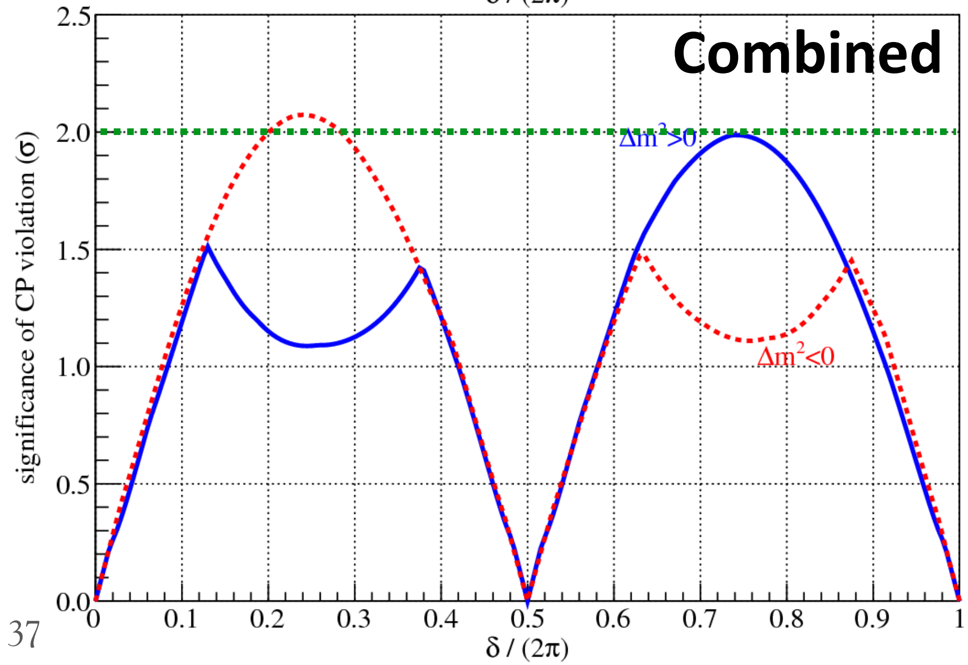
CP violation determination at the end of 2019. Even split of ν and $\overline{\nu}$ running at both expts.

For test scenario of $\sin^2(2\theta_{13})=0.095$, $\sin^2(2\theta_{23})=1$



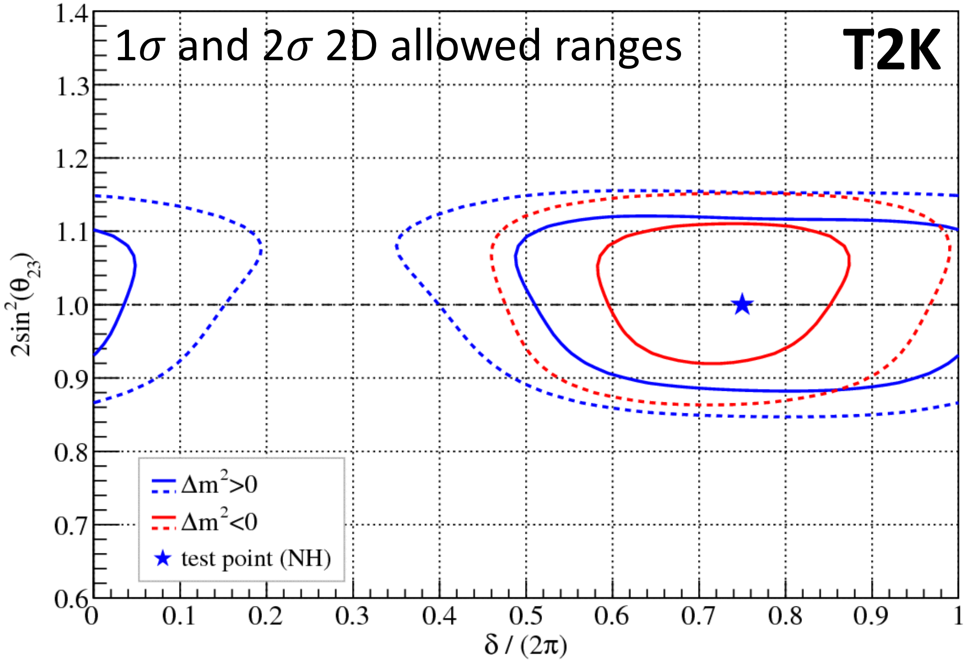


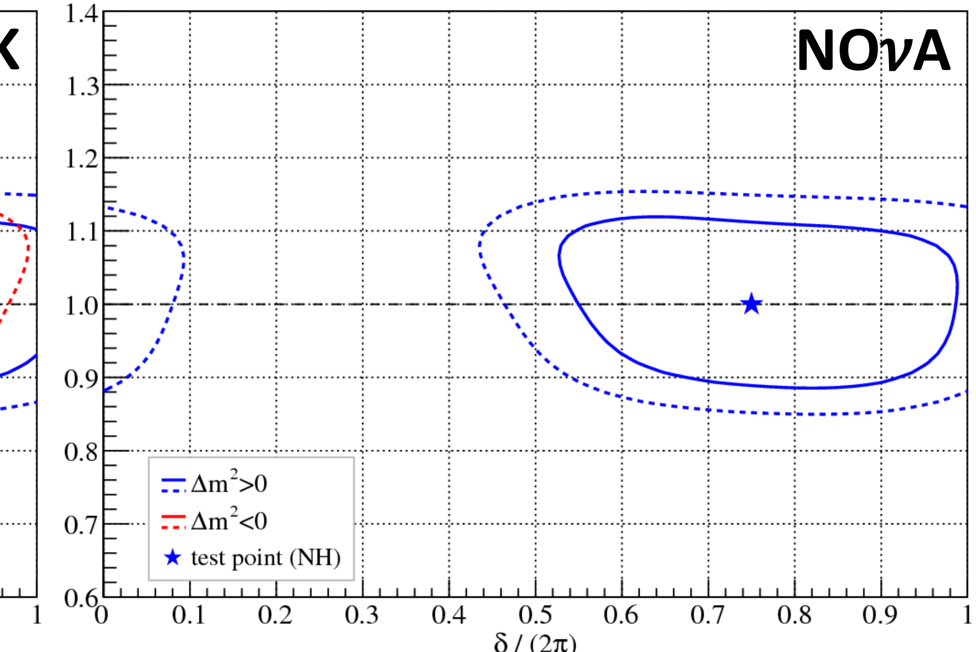
- **CPv tough all around!**
- Essentially **no coverage at 2σ**, but a good start over much of δ
- <u>Note:</u> unlike the hierarchy reach, this **can be arbitrarily hard**, depending on the true answer
- (In other words, these *must* go to zero significance at two points for *any* experiment.)



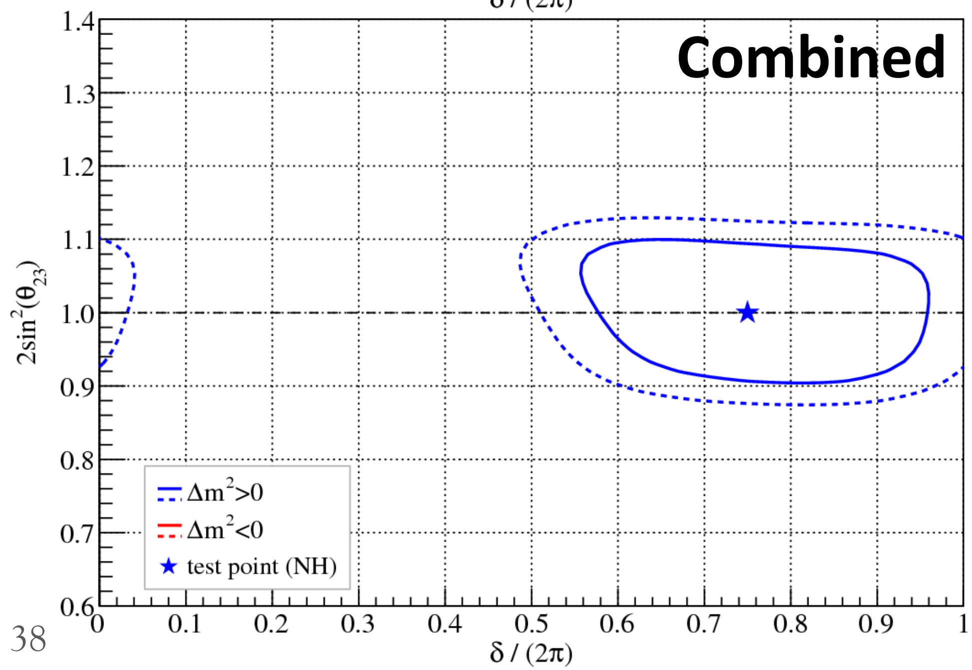
Simultaneous δ, θ_{23}, and hierarchy information expected at the end of 2019. Even split of ν, $\bar{\nu}$.

For starred point shown and $\sin^2(2\theta_{13})$=0.095



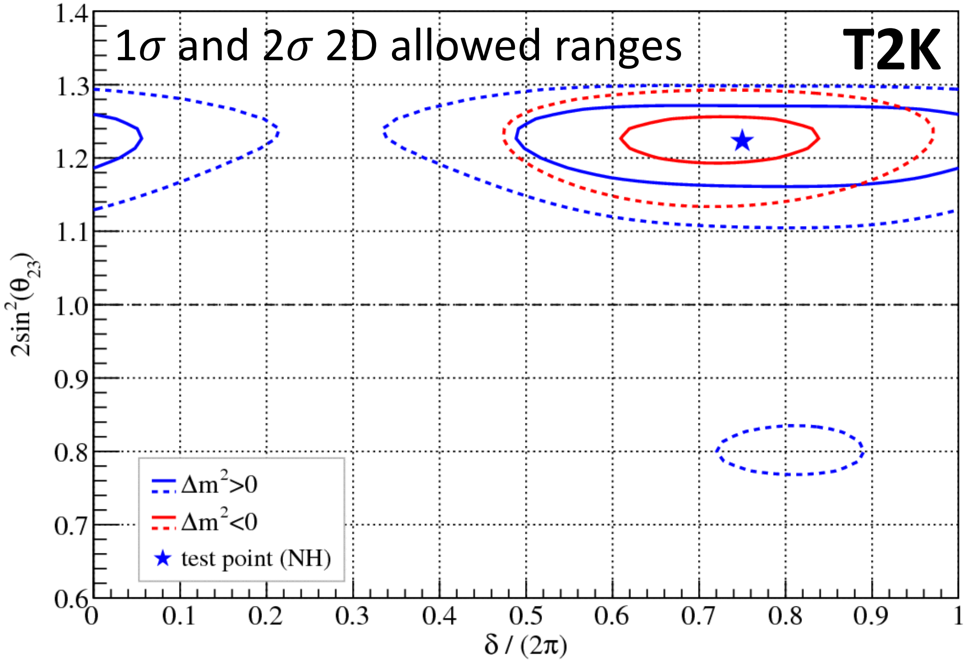


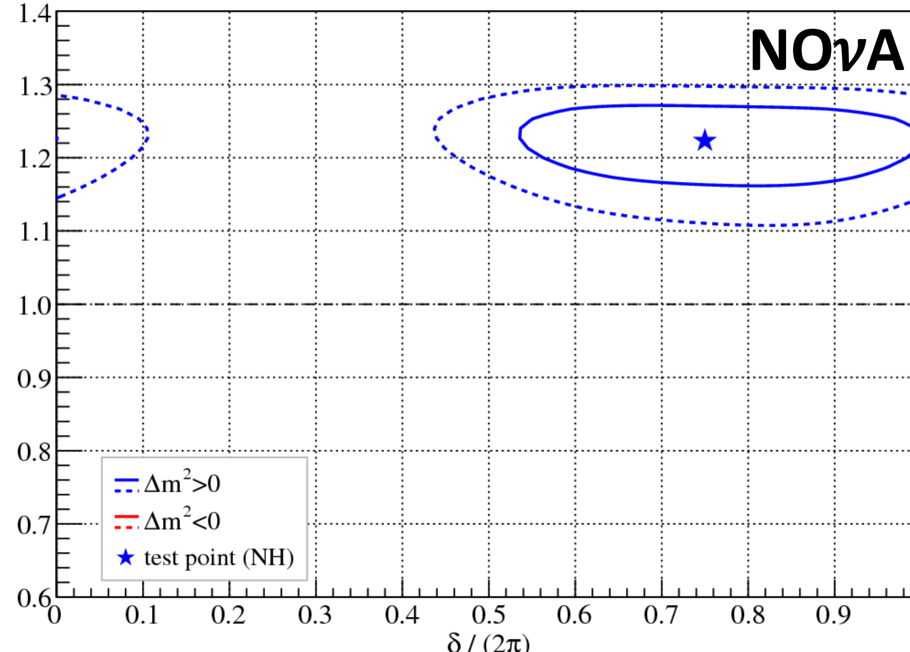
- **Maximal mixing scenario**
- These plots show the combined influence of ν_e **appearance** and ν_μ **disappearance** data
- A particularly favorable test point
- **Hierarchy resolved at >2σ** (no red contours remaining)
  (Actually >2.5σ, since $\Delta\chi^2$=6.18 sets the 2σ contours drawn in this 2D space.)



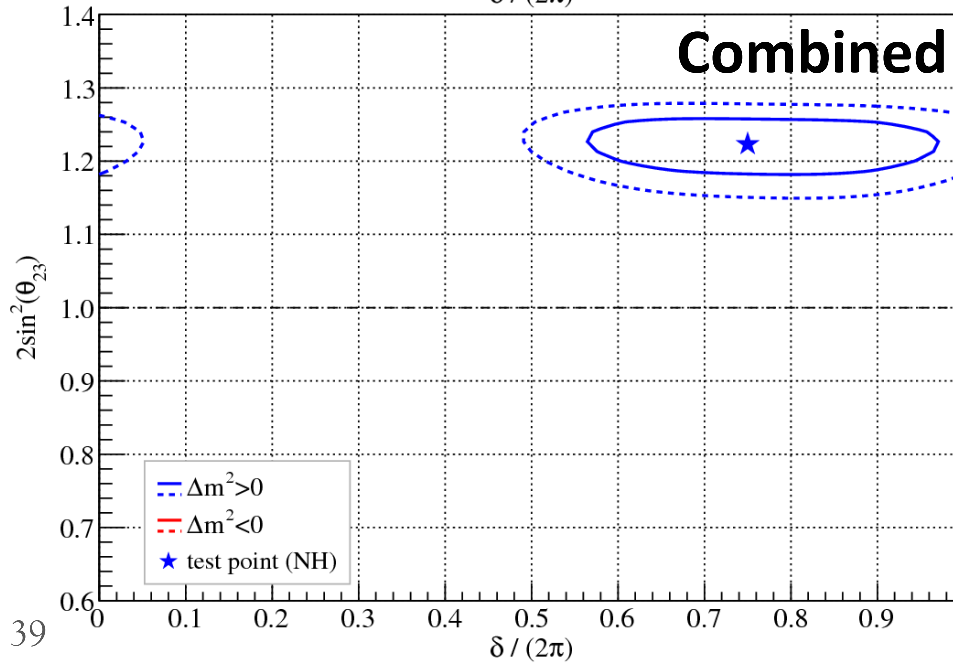
Simultaneous δ, θ_{23}, and hierarchy information expected at the end of 2019. Even split of ν, $\overline{\nu}$.

For starred point shown and $\sin^2(2\theta_{13})=0.095$



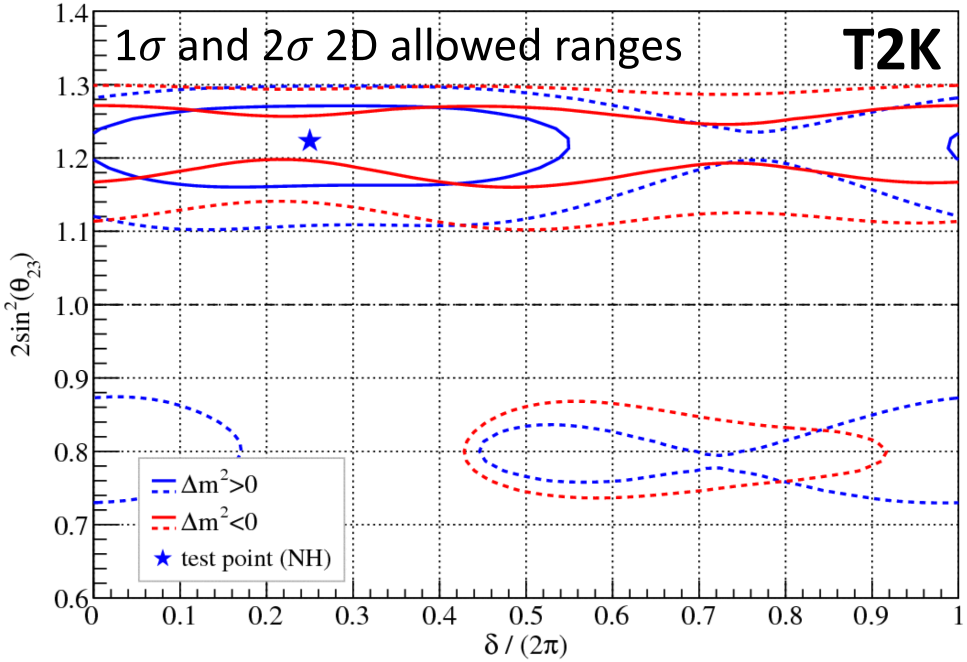


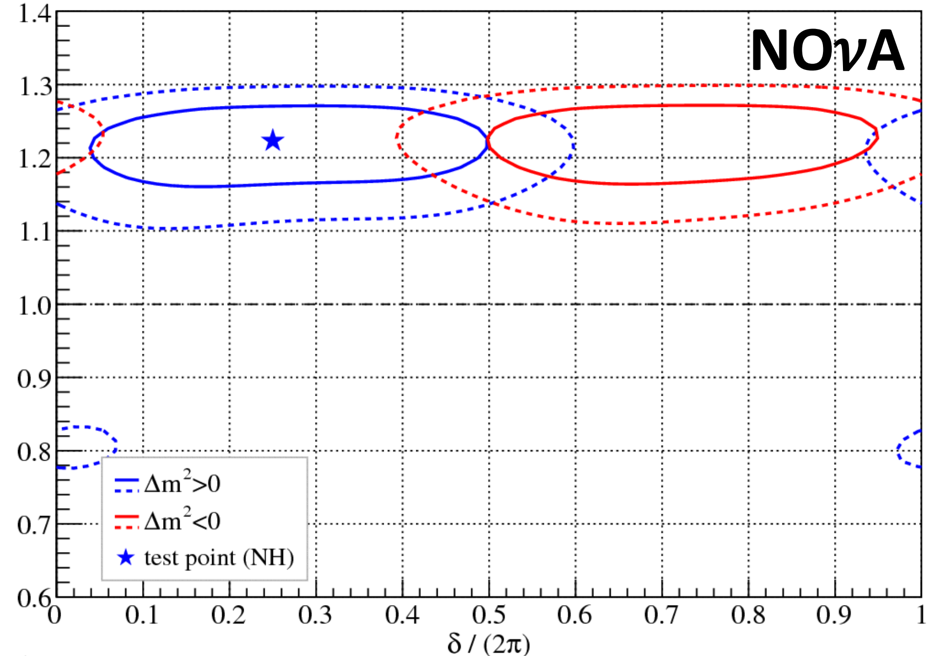
- **Non-maximal mixing scenario:** **$\sin^2(2\theta_{23})=0.95$, $\theta_{23}>\pi/4$**
- **Octant resolved** in NOνA and combined cases at $>2.5\sigma$.
  (Probably $>2\sigma$ in T2K; would need to check $\Delta\chi^2$ at the center of the little island.)



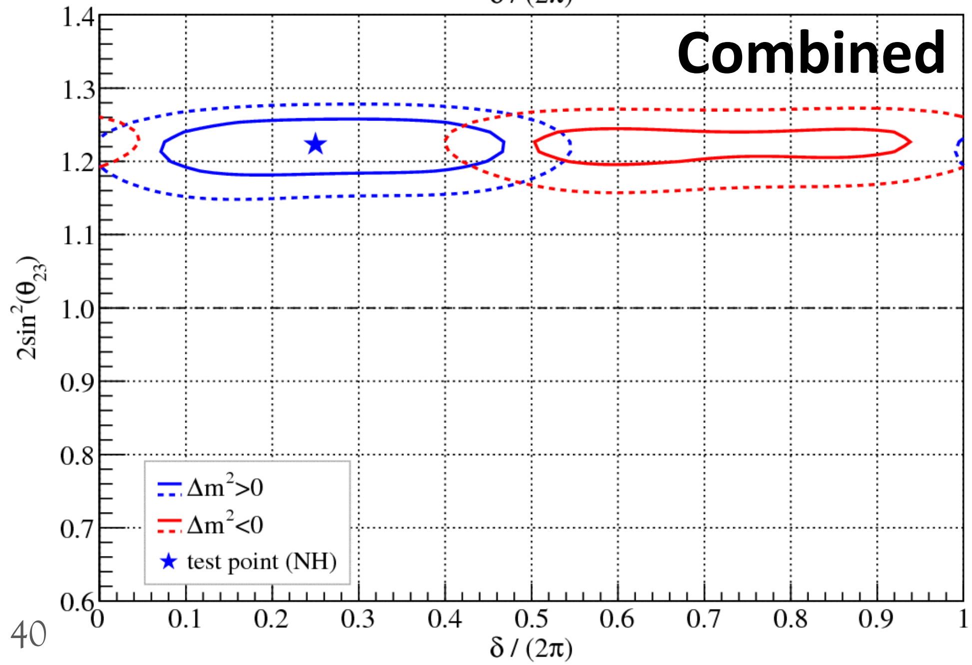
Simultaneous δ, θ_{23}, and hierarchy information expected at the end of 2019. Even split of ν, $\overline{\nu}$.

For starred point shown and $\sin^2(2\theta_{13})$=0.095





- **Non-maximal mixing scenario:**
  $\sin^2(2\theta_{23})$=0.95, $\theta_{23}>\pi/4$



- **…with unfavorable δ this time**
- **Octant still resolved** at >2.5σ, despite "degeneracy"
- ***This is a general point:*** *octant determination is largely insensitive to hierarchy and δ*

Longer-term, "ultimate" reach

- The preceding slides considered a nominal run of NOνA and T2K, through 2019.

- Relevance goes well beyond 2019, considering potential timescale for a 3rd generation experiment (particularly a Project-X-powered experiment)

- So, let's consider this scenario:
  - NOνA continues running at 14 kton × 700 kW for another 6 years (to 2025)
  - T2K continues running at 22.5 kton × 700 kW for another 6 years (to 2025)
  - NOνA achieves a further 20% sensitivity gain through analysis improvements
  - T2K achieves a further 10% sensitivity gain through analysis improvements

- This is, to some degree, the only scenario that matters as far as Project X is concerned…

The scenario

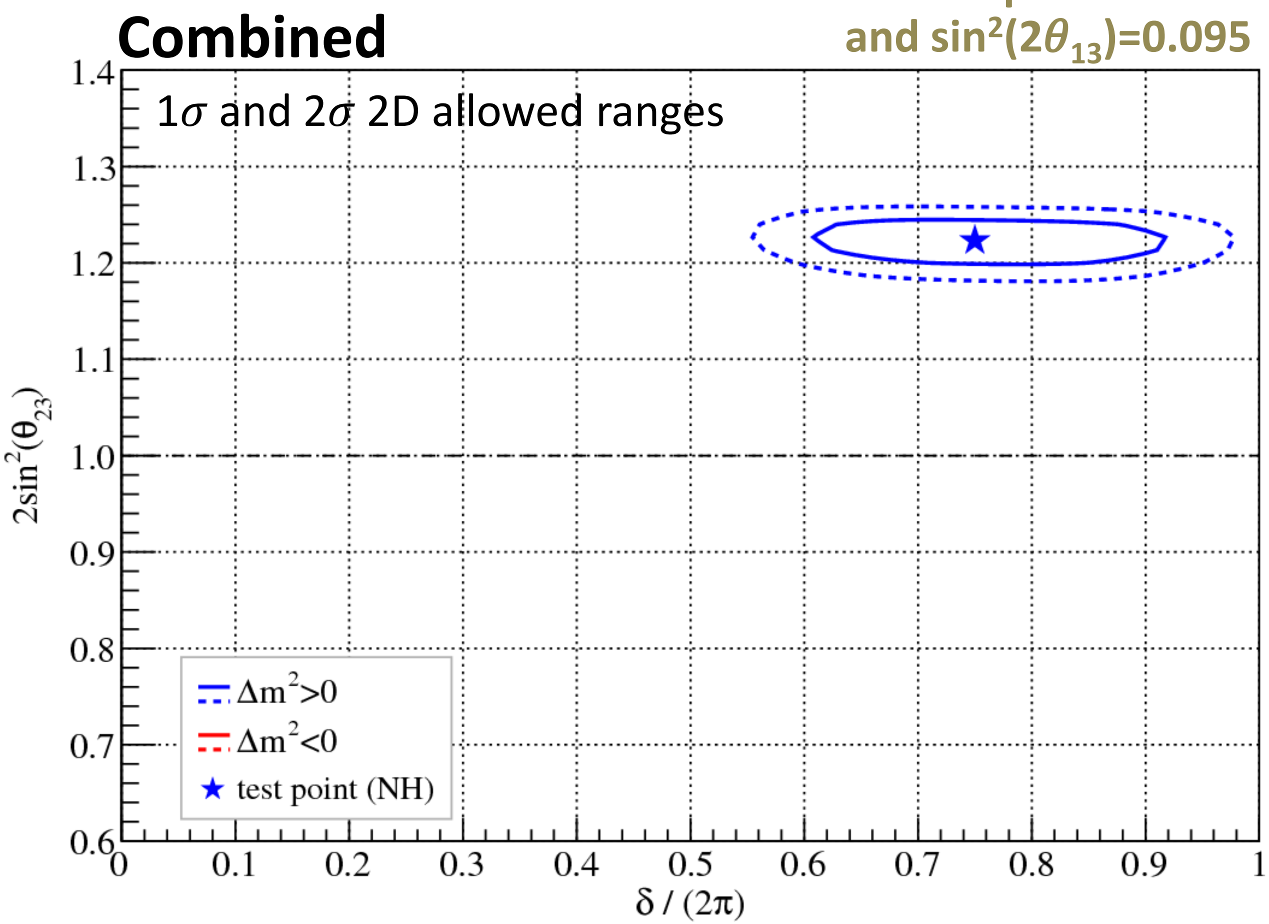
- NOνA continues running at 14 kton × 700 kW for another 6 years (to 2025)
- T2K continues running at 22.5 kton × 700 kW for another 6 years (to 2025)
- NOνA achieves a further 20% sensitivity gain through analysis improvements
- T2K achieves a further 10% sensitivity gain through analysis improvements

Expected contours for:

$\sin^2(2\theta_{23}) = 0.95$
$\theta_{23} > \pi/4$
δ favorable

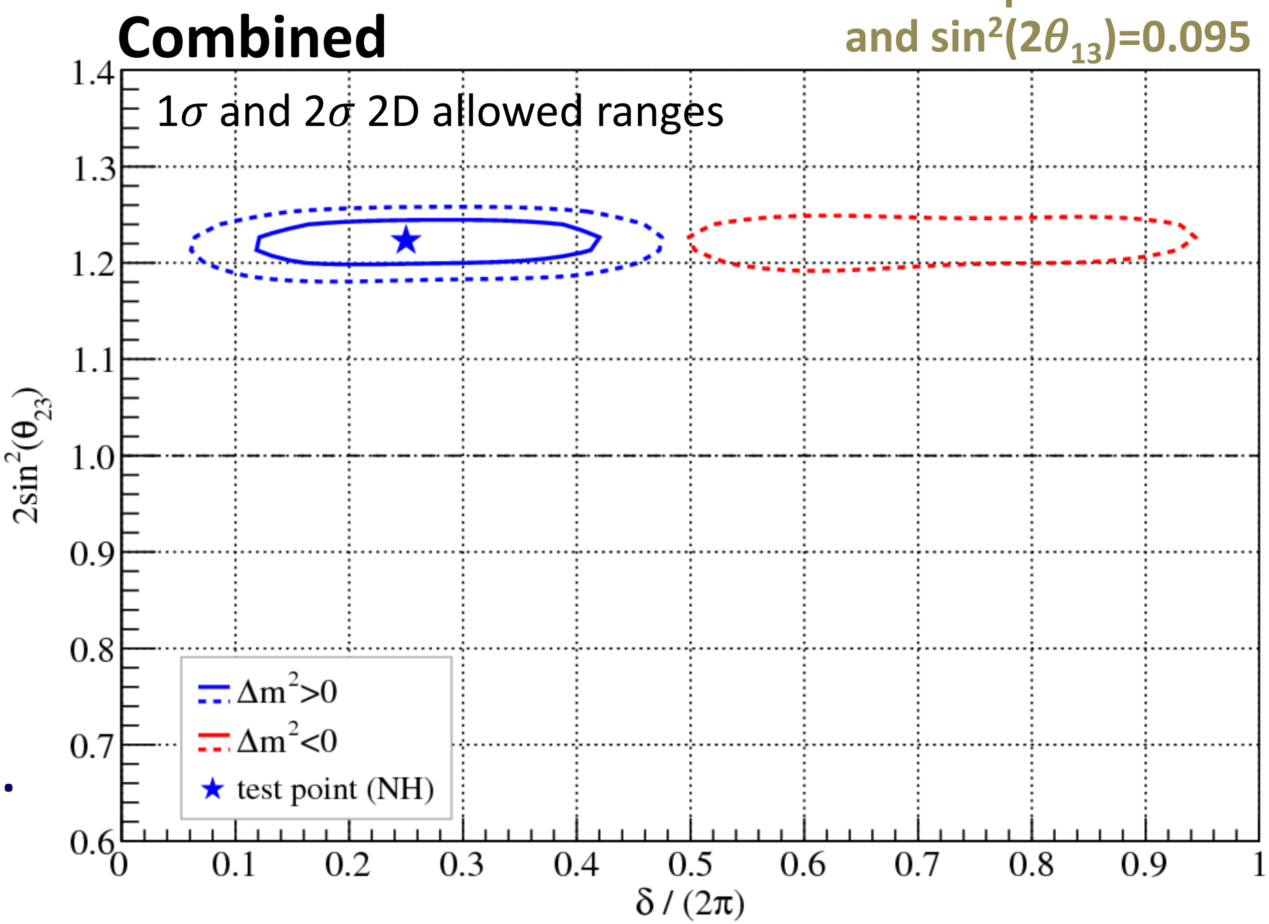
All targets determined at >2σ (much greater for some)

For starred point shown and $\sin^2(2\theta_{13})$=0.095



- **The scenario**
  - **NOνA continues running at 14 kton × 700 kW for another 6 years (to 2025)**
  - **T2K continues running at 22.5 kton × 700 kW for another 6 years (to 2025)**
  - **NOνA achieves a further 20% sensitivity gain through analysis improvements**
  - **T2K achieves a further 10% sensitivity gain through analysis improvements**

For starred point shown and $\sin^2(2\theta_{13})=0.095$



Expected contours for:

$\sin^2(2\theta_{23}) = 0.95$

$\theta_{23} > \pi/4$

δ unfavorable

Not bad:

CP conserving points and wrong octant ~excluded; wrong hierarchy still allowed.

- **The scenario**
  - **NOνA continues running at 14 kton × 700 kW for another 6 years (to 2025)**
  - **T2K continues running at 22.5 kton × 700 kW for another 6 years (to 2025)**
  - **NOνA achieves a further 20% sensitivity gain through analysis improvements**
  - **T2K achieves a further 10% sensitivity gain through analysis improvements**

Raw hierarchy sensitivity
maximal mixing scenario

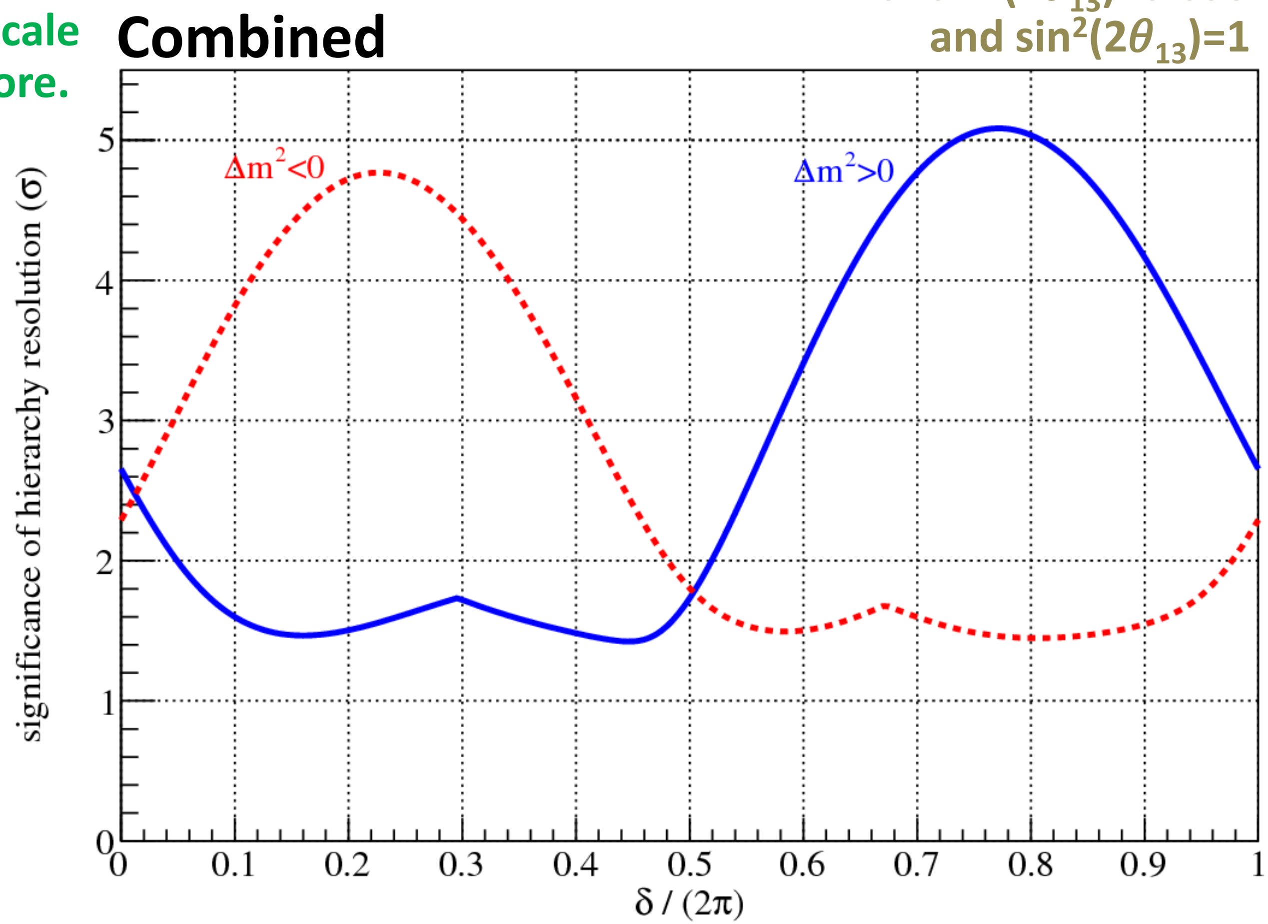
Best: 5.1σ

53% of δ range: >2σ
40% of δ range: >3σ

Everything >1.4σ: a good start.

Note: different vertical scale than before.

For $\sin^2(2\theta_{13})$=0.095 and $\sin^2(2\theta_{13})$=1



The scenario

- NOνA continues running at 14 kton × 700 kW for another 6 years (to 2025)
- T2K continues running at 22.5 kton × 700 kW for another 6 years (to 2025)
- NOνA achieves a further 20% sensitivity gain through analysis improvements
- T2K achieves a further 10% sensitivity gain through analysis improvements

Raw CPv sensitivity
maximal mixing scenario

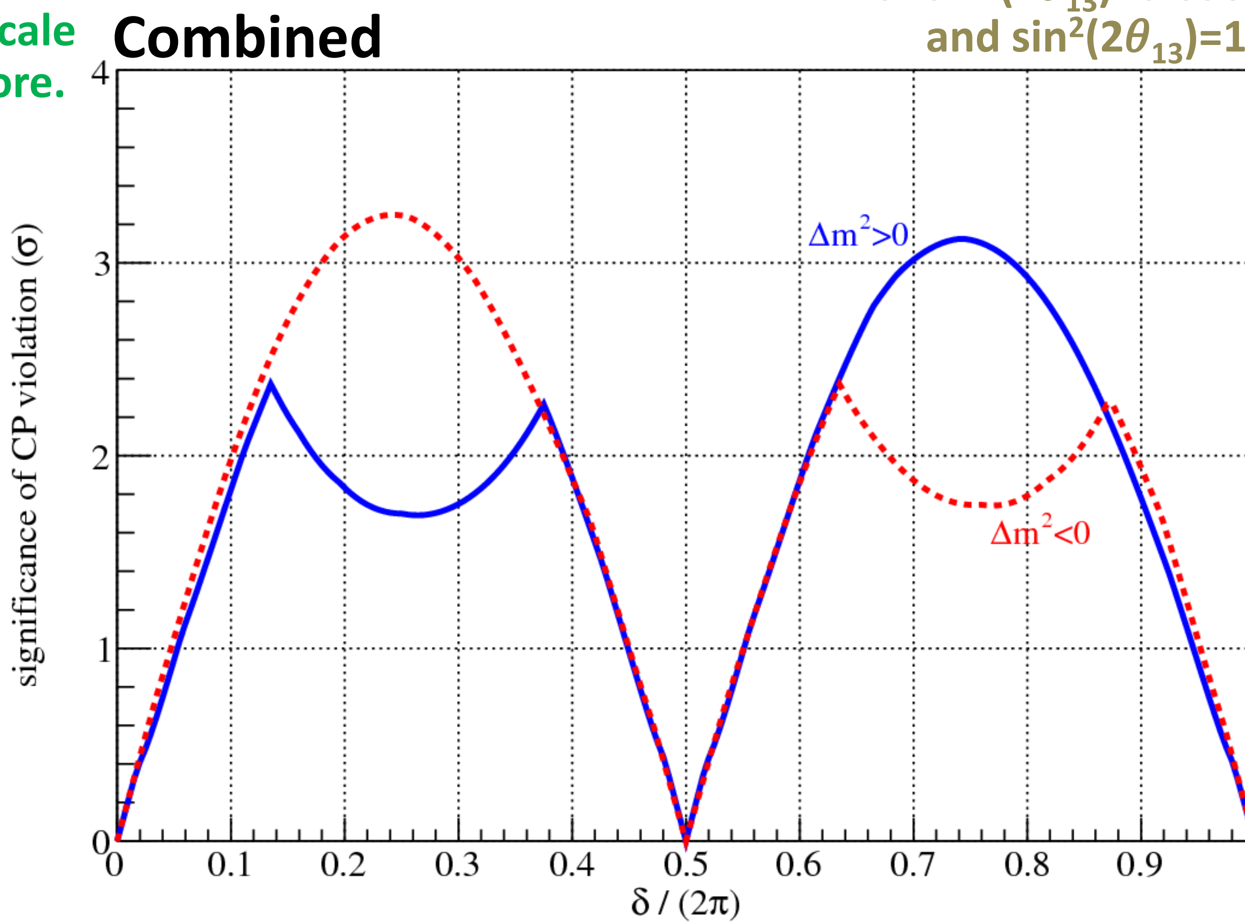
Best: 3.2σ

40% of δ range: >2σ
10% of δ range: >3σ

No mininum.
(Can be arbitrarily hard! A future experiment can't have too much CP sensitivity.)

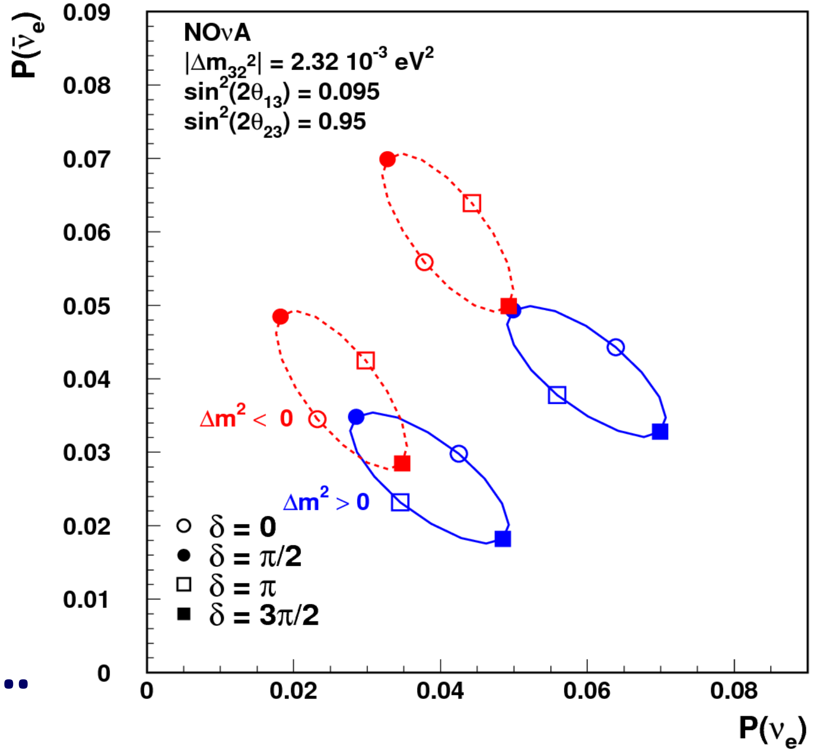
Note: different vertical scale than before.

For $\sin^2(2\theta_{13})$=0.095 and $\sin^2(2\theta_{13})$=1



A few words on run plans

- Too many scnearios to enumerate, so some rules of thumb…
  - If you knew that $\sin^2(2\theta_{23})=1$, then ν running is generally best
    But, you don't – and won't – know that…
  - If $\sin^2(2\theta_{23})<1$ (*even slightly, say: 0.98*), some $\bar{\nu}$ running is needed ⟶
    (A few outlier cases prefer only $\bar{\nu}$ or ν, but not most)
  - A mixed run plan is generally better for both T2K and NOνA, but the T2K choice is less critical if NOνA runs mixed
    (Biggest influence of T2K in the combined reach is in hierarchy degeneracy breaking, which can be done with ν-only running)



- There are other reasons to run mixed…
  - $\nu+\bar{\nu}$ over-constrains the atmospheric sector
  - Standard 3ν formalism okay? CPTv (effective or otherwise)?
- Run plan decisions are temporally coarse by their nature
  - Start with a slug of ν data
  - *Note:* data-driven run plan changes make future statistical analysis trickier

Closing thoughts

- End of 2019: **NOνA can get hierarchy** at 95% C.L. for **~37% of δ range**
  (exact fraction depends on θ_{23})
- In combination with T2K, **this metric doesn't change.**
  But: the other ~63% of δ values get a head start of ~1σ for future combined fits
- **In super scenario** (2025 + analysis gains), the combination reaches:

Hierarchy:
40% of δ range: >3σ
53% of δ range: >2σ
100% of δ range: >1.4σ

CP violation:
10% of δ range: >3σ
40% of δ range: >2σ

(Exact fractions depend on θ_{23})

- An unambiguous **demonstration of CP violation**…
  - *…**can be arbitrarily hard**, depending on what Nature has chosen*
  - *…requires **considerably more confidence** than the hierarchy determination (which is not a "discovery" result)*
  - *…is **tough for T2K+NOνA***
- Future experiments should **emphasize CPv reach.**
  *As long as we've got LBL+atm. expts., we'll get the hierarchy **(if we aren't already there in a few years!).** Also, **LBNE scenarios should be shown as combined fits**: recall the "non-linear" benefits in T2K+NOνA combination*